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Quantitative paleoenvironmental analysis of carbonate platform sediments on the Marion Plateau (NE Australia, ODP Leg 194)

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by

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of the requirements for the degree of
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ABSTRACT

The Marion Plateau is a carbonate-platform complex on the passive northeast Australian margin. During ODP Leg 194, a series of eight sites, on two transects, was drilled through Oligocene to Holocene mixed carbonate and siliciclastic sediments that record the depositional history of the Marion Plateau. Major sediment constituents, including benthic foraminifers, were counted from thin sections made from samples taken from three drilling sites: bryozoan-dominated northern highstand platform site 1193 and northern lowstand ramp site 1194, and coralline red algae-dominated southern platform site 1196.

Quantitative multivariate analysis of benthic foraminiferal assemblages revealed three paleoenvironmentally relevant groups of taxa. The first group, dominated by *Amphistegina* and *Lepidocyclina*, was found at all three sites and is interpreted to be representative of euphotic open-shelf deposition in less than 50 m water depth. The second group was dominated by *Cycloclypeus*, *Operculina* and planktonic foraminifers. This group was found at all three sites, but was more common from sites on the northern platform and is interpreted to represent deposition in deep, oligophotic water, in greater

than 50 m water depth. The third group, consisting of soritids, alveolinids, *Austrotrillina* and *Flosculinella*, was found only in sediments from the southern platform and is interpreted to represent deposition in a restricted, shallow-marine environment, in less than 20 m water depth, consistent with a sea-grass meadow. These three groups of taxa record changing paleoenvironments on the Marion Plateau, and reveal the depositional histories of the Marion Plateau's carbonate platforms.

Introduction

A number of important changes occurred in the ocean-atmosphere system during the Miocene. This epoch is considered a time of transition between the Paleogene oceans and the oceans as we know them today. The Miocene was an epoch characterized by warm climate and high sea level, which transitioned into the glacial-interglacial cycles that are a hallmark of Neogene climate history (Vincent *et al.,* 1985; Holbourne *et al.,* 2004). Some features of modern ocean circulation that were established in the Miocene include strong meridional and vertical thermal gradients and the dominance of high-latitude deep-water sources. The Middle Miocene, especially, was a time during which global climate changed to a colder mode (Hodell and Kennett, 1985; Miller *et al.,* 1987; Flower and Kennett, 1994; Turco *et al.,* 2001; Zachos *et al.,* 2001; Holbourne *et al.,* 2004). This climatic change was not smooth and unidirectional; rather, it was oscillatory (Li and McGowran, 1997).

Several hypotheses explain the Miocene climate transition (Flower and Kennett, 1994; Raymo, 1994). The tectonic isolation of the Antarctic continent, caused by the northward motion of Australia (beginning at about 35 mya) and South America (beginning approximately 12 mya), allowed initiation of the Antarctic Circumpolar

Current (Kennett, 1977). This effectively isolated the Antarctic continent from heat transport from low latitudes, allowing the local climate to cool substantially.

Ice accumulation on the Antarctic continent is reflected in the record of the ratios of oxygen isotopes preserved in foraminifers in deep-sea sediments worldwide (e.g., the oxygen isotope curve of Zachos *et al.,* 2001). Oxygen isotope records are used as a proxy for global ice volume throughout the Cenozoic (Zachos *et al.,* 2001). Water molecules containing light oxygen isotopes are preferentially removed from the ocean during evaporation processes. In glacial times, these 'light' water molecules are stored on continents in the form of ice, and are thus removed from ocean circulation, enriching the remaining water in heavy oxygen isotopes. The progressive enrichment of the oceans in the heavy oxygen isotopes, particularly in Middle Miocene times (i.e., between 15 and 12 Ma), is a compelling line of evidence for cooler climates beginning at this time (Kennett and Shackleton, 1975).

The oxygen isotope record is not the only evidence indicating that Antarctic ice sheets became permanent features of Earth's surface during the Middle Miocene. Geomorphological data from the Antarctic continent strongly suggests that erosive glaciers reached their current positions in the Middle Miocene, which implies an enduring East Antarctic Ice sheet since that time (Marchant and Denton, 1996). Benthic foraminiferal assemblages on continental shelves also shifted with falling sea level, as depth zonations on continental shelves changed (Li and McGowran, 1997).

That Antarctic ice sheets grew substantially during the Miocene is now well accepted by the scientific community. What is not as well known is the rate at which the

ice sheets grew. Or, from a different perspective, how quickly did sea level fall during the Miocene, and by how much?

Study Area

The Marion Plateau is part of the slowly subsiding, passive, northeastern Australian margin and, as such, is an ideal location to study the causes and effects of sea-level change on continental margin sediments. The northeast Australian margin, including sites on the edge of the Marion Plateau, was previously drilled during ODP Leg 133 (McKenzie and Davies, 1993). The Marion Plateau and its associated carbonate platforms are located between 18°S and 23°S and is the most southerly of the northeast Australian marginal plateaus. The Marion Plateau is bounded by the Townsville Trough to the north, the Cato Trough to the east and the south-central Great Barrier Reef to the west (see map, Fig 1).

The northern highstand platform, Site 1193 (Fig. 1, 2), is located on the Marion Plateau approximately 80 km east of the south-central Great Barrier Reef, in 348 m of water. This site was positioned with the goal of recovering sediment sequences that would reveal the Middle Miocene northern carbonate-platform history of the Marion Plateau (Shipboard Scientific Party, 2002). Drilling on the northern highstand platform recovered three cores (1193 A, B and C), which penetrated to depths of 515, 128 and 548

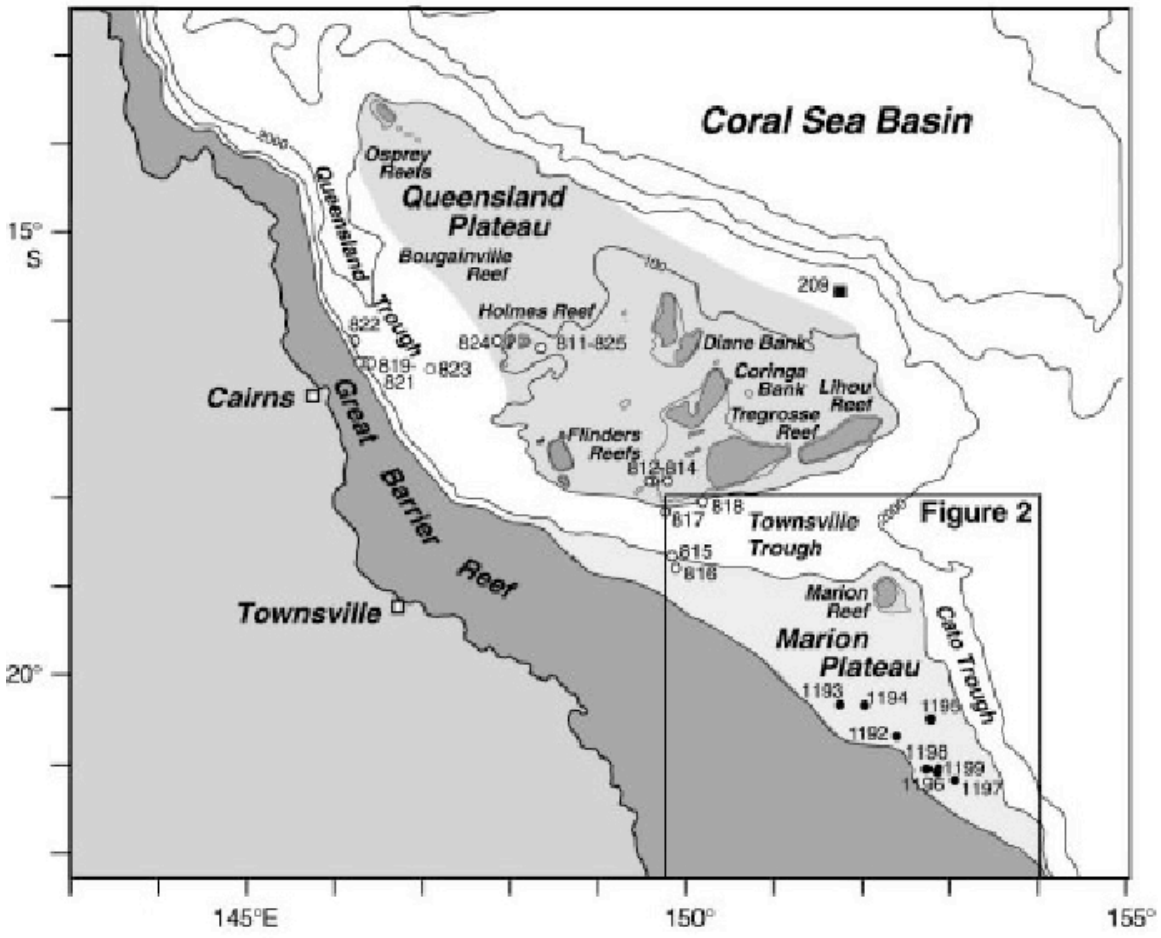


Figure 1 - Map of northeastern Australian margin. The Marion Plateau, including ODP Leg 194 drill sites are highlighted in the lower right (from Shipboard Scientific Party, 2002).

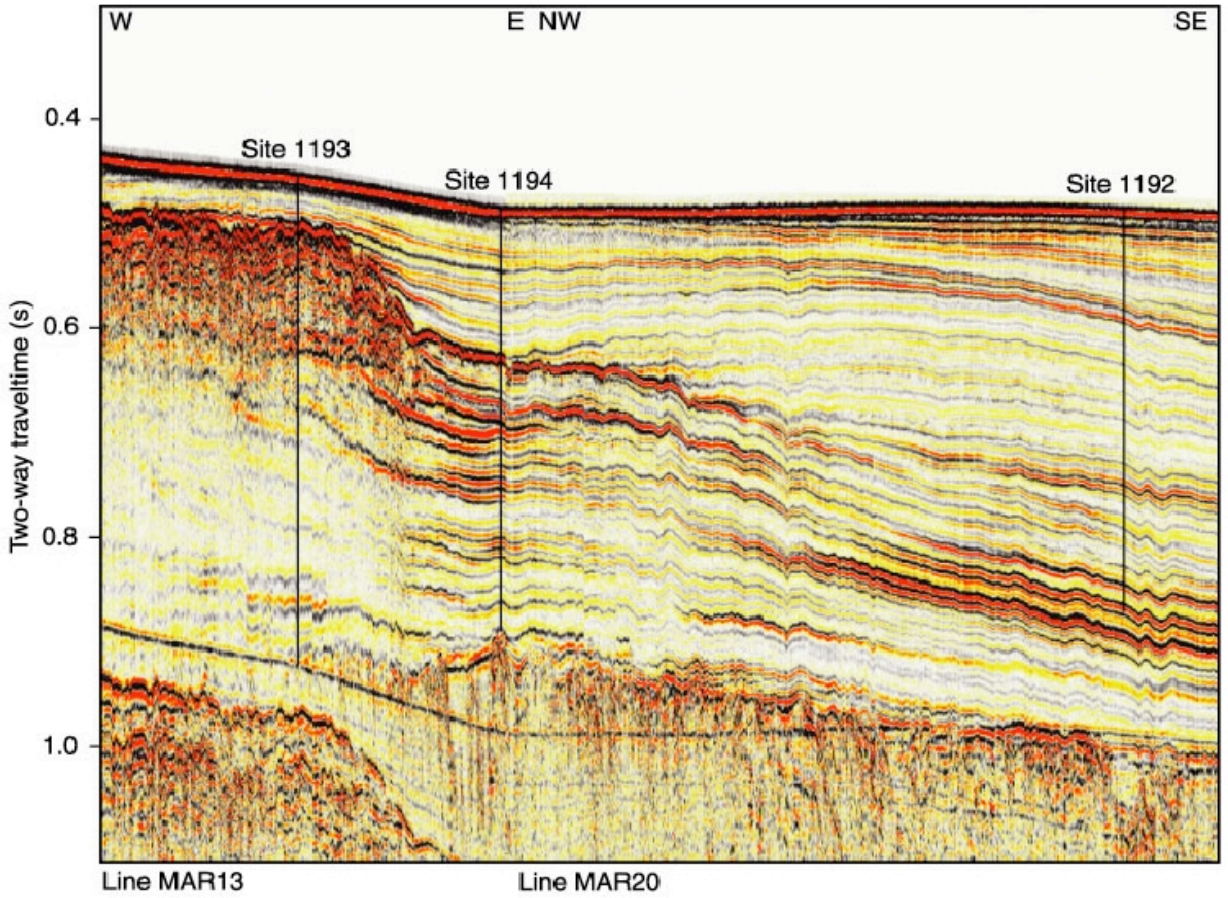


Figure 2 – Seismic profile of northern Marion Plateau, showing the northern highstand platform drilled at Site 1193 and the northern lowstand platform drilled at Site 1194 (from Shipboard Scientific Party, 2002)

meters below sea floor (mbsf) respectively, and which provide a record of the total thickness of the northern platform near the platform edge. Recovery of sediments in this location varied between the cores but was on average ~20% (Shipboard Scientific Party, 2002). A significant proportion of the sediments on the northern highstand platform include siliciclastic grains, indicating that a terrestrial influence was important at this site during the Miocene.

Site 1194 (Fig. 1, 2), the northern lowstand ramp site, is located approximately 20 km east of the highstand platform and was drilled with the objective of investigating the growth history of the northern platform as recorded in adjacent marginal slope sediments (Shipboard Scientific Party, 2002). A prominent seismic horizon overlies these slope sediments and is interpreted as being traceable to the surface unconformity on the northern platform (Fig. 2). Thus, the Shipboard Scientific Party (2002) hypothesized that this seismic horizon represents the top of an *in situ* lowstand ramp deposited in the sea-level lowstand following the Middle Miocene eustatic sea-level fall. Two holes (1194A and 1194B) were drilled at Site 1194. Recovery was excellent in the first hole, which penetrated to 117.4mbsf. The second hole, 1194B, however, recovered only approximately 7.6% of sediments. In fact, drilling at Site 1194 was abandoned at 169 mbsf due to low recovery.

Southern Platform site 1196 (Fig. 1, 3) was drilled into the top of the southern carbonate platform on the Marion Plateau in 304 m of water. The site is located approximately 20 km east of the Great Barrier Reef margin. The southern platform was drilled to provide information on the initiation and facies development of the southern

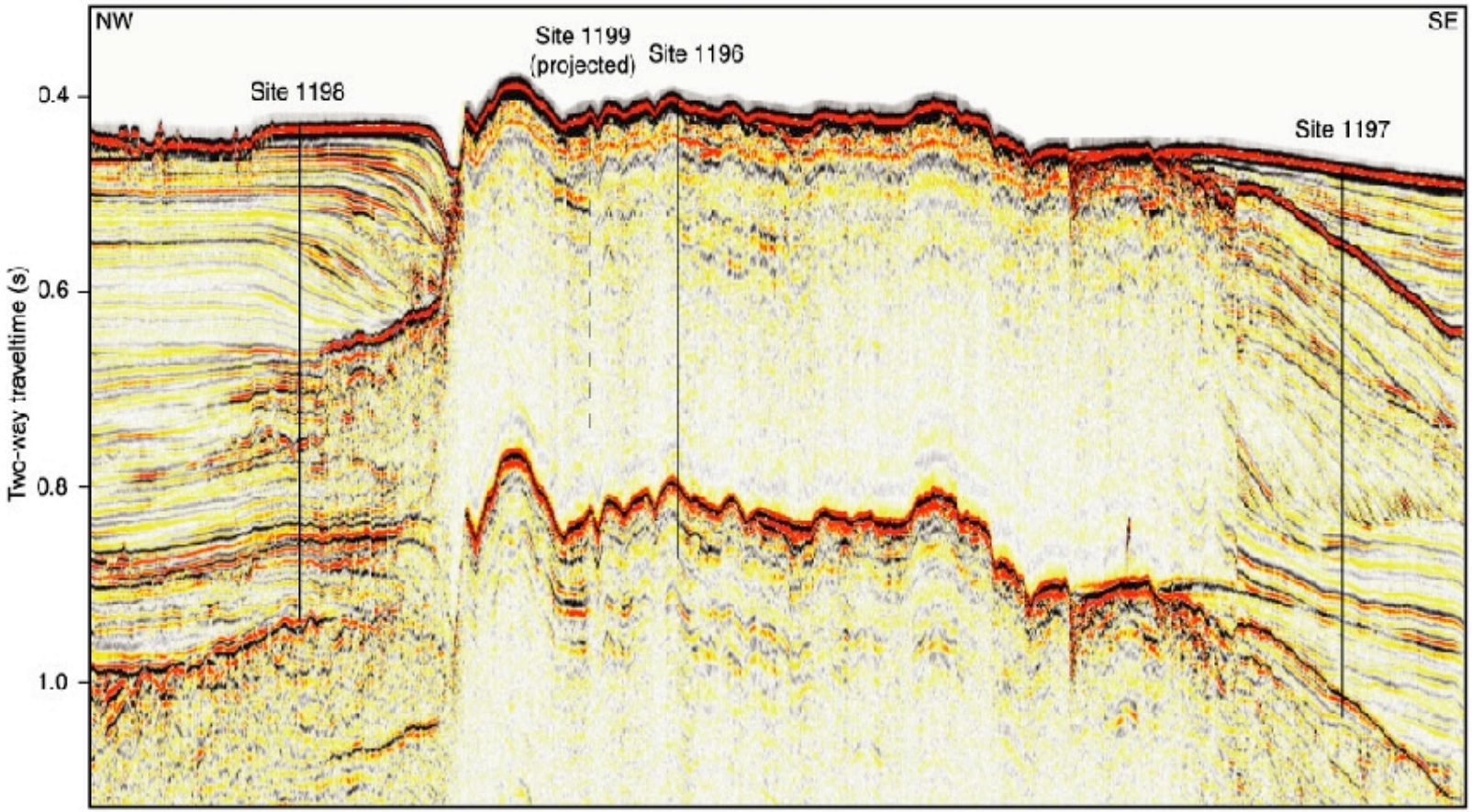


Figure 3 – Seismic profile of southern Marion Plateau showing the southern platform drilled at site 1196 (from Shipboard Scientific Party, 2002).

carbonate platform (Shipboard Scientific Party, 2002). Two holes were drilled: 1196A and 1196B, through a 663 m sequence of carbonate platform sediments (Shipboard Scientific Party, 2002). Recovery of platform sediments was extremely poor, with only 86 m of cored sediments recovered, for an average of approximately 13%.

The Marion Plateau and Sea Level

Carbonate platforms and their slopes are sensitive indicators of sea-level variations. Traditional carbonate sequence-stratigraphic models hold that carbonate platforms record growth during sea-level highstands and shut down during sea-level lowstands (Emery and Myers, 1996). Sampling these platforms records sea-level change in a "dipstick" fashion (Shipboard Scientific Party, 2002). The margins of carbonate platforms and associated slopes record sea-level variations as alternations of shallowing and deepening sequences.

Drilling on the northern Marion Plateau (sites 1193 and 1194) provided an excellent opportunity to assess the magnitude of the second-order eustatic sea-level fall during Foraminiferal Zones N12-N14 (Shipboard Scientific Party, 2002). Geoscientists have been attempting to resolve the Middle Miocene sea-level fall for years both generally (Haq *et al.,* 1987, Miller and Mountain, 1996; Miller *et al.,* 1998), and using Marion Plateau sediments, specifically (Pigram *et al.,* 1992).

Sequence-stratigraphic and facies relationships from Site 1193 and 1194 allowed an estimate of the magnitude of the sea-level fall to be made. By measuring the height differential between the top of what is interpreted to be a second-order highstand platform complex (drilled at Site1193) and the top of an interpreted second-order lowstand ramp deposit (drilled at Site 1194), decompacted from present-day sediment and water-column loads, an estimate of the N12-N14 sea-level fall was calculated (John *et al.,* 2004). Accounting for overall regional tectonic subsidence, and combined with constraints from oxygen isotope analysis data, this calculation resulted in an estimate of 50 +/- 5 m for the late Middle Miocene sea-level fall (John *et al.,* 2004). This result takes into account paleowater depths provided by qualitative shipboard analysis of benthic foraminiferal assemblages.

The Marion Plateau sea-level calculation is based upon several assumptions. The first is that the basement rock beneath the plateau is of infinite flexural strength, or, in other words, that no differential subsidence occurred on this margin. This assumption is supported by the presence of undisturbed and constantly dipping sediments, the short distance (~12km) between the highstand and lowstand sites on the northern platform (Fig. 2), and the absence of major faulting in gathered seismic data (Isern *et al.,* 2001). Platform erosion on the highstand platform was not taken into consideration in this calculation, however, which presents a potential for error in the results. If the northern platform was subaerially exposed sufficiently for the locus of sedimentation to move down the slope, erosion at in this location was likely. Adjusting for possible erosion would increase the estimate for sea-level fall (Isern *et al.,* 2001).

Another assumption in the calculation is that drilling operations at the lowstand ramp site penetrated rocks that record the lowest sea level; this may not have been the case (Isern *et al.,* 2001). If the sediments cored at the top of the 'ramp' were not deposited during the lowest lowstand of sea level, the sea-level fall calculation would be in error, underestimating the sea-level change.

The final, and most important, assumption of the sea-level change calculation, is that the hypothesized lowstand carbonate ramp deposit was, indeed, deposited *in situ*, and not as a result of transport of non-lithified platform sediments from the nearby highstand platform. It is hypothesized that currents have been a major factor in controlling and maintaining sedimentary architecture on the Marion Plateau (Shipboard Scientific Party, 2002). Shipboard analysis of Site 1194 sediments did not confirm autochtonous sedimentation in this location, despite the suggestion of'ramp' deposit morphology in seismic stratigraphy. Further work is required to determine whether or not euphotic sediments at Site 1194 were emplaced by transport from the nearby northern carbonate platform.

Paleoenvironmental Analysis

Analyses conducted shipboard during Leg 194 indicated Miocene platform accretion in cool-subtropical climatic conditions, with paleowater depths ranging from subaerial to subeuphotic (Shipboard Scientific Party, 2002). In the late Middle Miocene, carbonate-bank productivity diminished rapidly when sea level fell between 11 and 7 Ma (Isern *et al.,* 2001). Strontium-isotope dating of bioclasts (primarily mollusk shells) from the top of the northern highstand platform indicates an age range of from 10.6-12.9 Ma (Ehrenberg *et al.,* 2003). Age control is very poor at the highstand platform site, due to poor core recovery, dolomitization and the lack of planktonic microfossils in the recovered sediments (Wei, 2004). Despite these problems, termination of the highstand carbonate platform (the top of lithologic Unit II) is estimated to be Middle Miocene time, and that platform sediments were assumed not to have significantly eroded as sea level fell in the Middle Miocene (Wei, 2004). Similarly, age control is also poor at Site 1196, in part due to abysmal recovery of platform sediments.

Benthic foraminiferal assemblages, which are preserved in Marion Plateau platform rocks and sediments, are an excellent tool for understanding and interpreting the paleoenvironmental history of the Marion Plateau (Shipboard Scientific Party, 2002). Benthic foraminifers comprise a diverse taxonomic group that has been widely studied in ecological and paleoecological projects. Benthic foraminiferal taxa in the Indo-Pacific region are well studied and their distributions, environmental ranges and ecological

tolerances are fairly well known (Chaproniere, 1981, 1983, 1984; Betzler and Chaproniere, 1993; Chaproniere and Betzler, 1993; Betzler *et al.,* 1997; Hohenegger, 1999, 2000, 2004; Hottinger, 1997; McGowran and Li, 2000).

Large, morphologically complex benthic foraminifers, informally classed as "Larger Benthic Foraminifera" (LBF) are important constituents of the rocks and sediments recovered from the Marion Plateau. LBF are not a separate taxonomic entity, rather they are scattered through several superfamilies and are sometimes quite closely related to smaller forms (Chaproniere, 1984). Extant LBF host a wide variety of algal endosymbionts, including diatoms, rhodophyceans, chlorophyceans and dinoflagellates, in a mutualistic relationship resembling that of corals and their zooxanthellae (Lee, 1998). It is commonly suspected that extinct benthic foraminifers of similar morphological complexity hosted endosymbionts in a similar manner. For example, a variety of morphological adaptations seen in fossil LBF are regarded as adaptations to better channel light through the foraminifer's test to the symbionts (Haynes, 1965; Hohenegger, 1999).

Because their photosynthetic endosymbionts require light, LBF occur in the euphotic and oligophotic zones of tropical and warm-temperate seas (Hohenegger, 2004). Pomar (2001) distinguishes between euphotic (high light), oligophotic (low light) and photo-independent carbonate-producing biota, and the effects that these different biota have on the resulting carbonate structures that they produce.

Hallock (1981) has shown that the mixotrophic lifestyle employed by LBF is most beneficial in oligotrophic conditions. As in corals, the advantages of algal symbiosis

include enhancement of calcification, uptake of host metabolites by the endosymbiont, and energy in the form of carbohydrates and lipids produced by photosynthesis (Hallock, 1999). Mixotrophy allows LBF taxa to colonize and thrive in shallow-water marine environments where nutrients and food supply are scarce. Indeed McConnaughey and Whelan (1997) postulate that calcification in these organisms promotes photosynthesis by providing CO_2.

Trophic resources (*sensu* Hallock 1987) include inorganic nutrients, trace elements and organic carbon and are important factors influencing the distributions and environmental tolerances of LBF taxa (Langer and Hottinger, 2000; Hohenegger, 2004). Trophic resources affect the depth distributions of LBF in two ways. Firstly, increased nutrients stimulate growth of phytoplankton, which reduces water transparency and therefore decreases the depth at which LBF can photosynthesize. Secondly, trophic resources can affect the abilities of these mixotrophic protists to compete with heterotrophs for space in a nutrified environment.

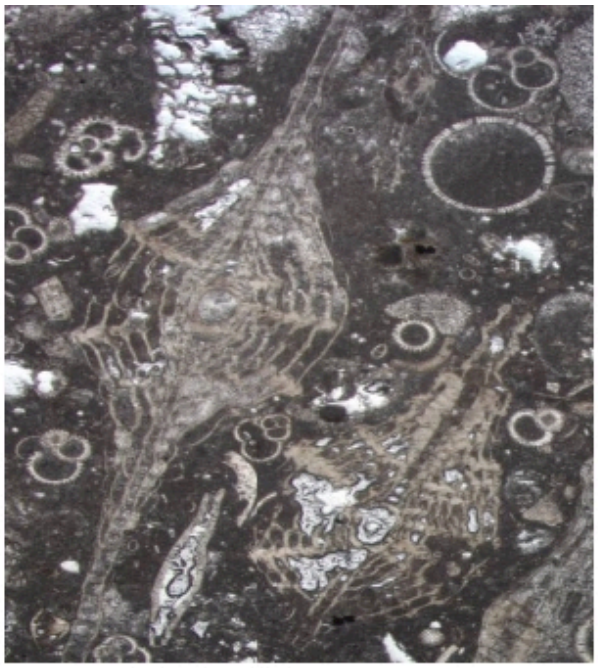
Morphologic variation among conspecific benthic foraminifers is correlated with environmental parameters, including temperature, hydrographic energy, light availability and carbonate-saturation state (Boltovskoy *et al.,* 1991; Hottinger, 1997; Hallock, 1999; Hohenegger, 2000, 2004). LBF produce thinner, flatter tests when light availability is low, for example, in the oligophotic zone. These thinner, flatter tests are also more delicate, and cannot withstand a great deal of hydrodynamic energy. Conversely, in shallower water, where light limitation is not problematic, LBF can produce thicker tests, which protect the protist from mechanical damage due to the increased hydrodynamic

energy in shallow waters (Hohenegger, 2000). These morphological variations, as well as depth-dependent species associations, mean that LBF are extremely useful for depth determination in shallow marine environments (Hohenegger, 2004).

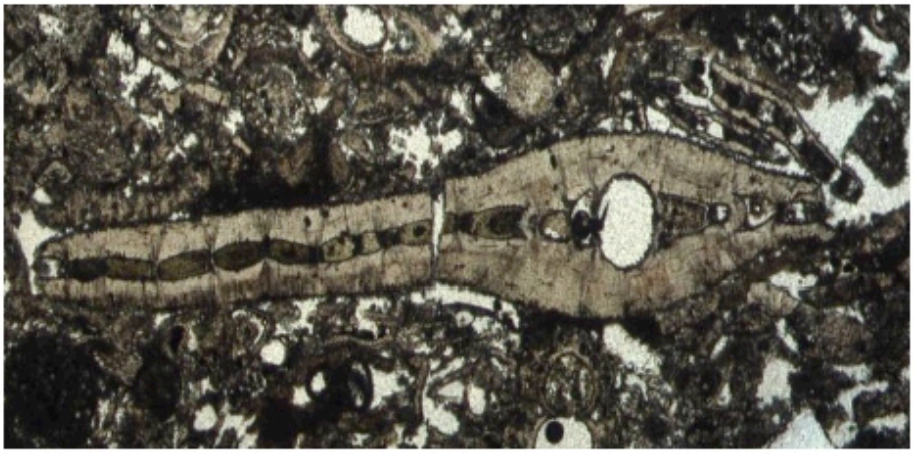
Of the LBF indicator taxa utilized in this project, several are now extinct while others remain extant today. Probably the best-studied LBF genus still extant is *Amphistegina* (Fig. 4A), which has been studied in a variety of settings for a variety of purposes (e.g., Hallock, 1981, 2000; Hallock *et al.,* 1986). The environmental tolerances and distributions of various members of the Amphisteginidae are well known: they are found worldwide in shallow tropical to sub-tropical seas. The various species found within the *Amphistegina* genus are known to have different test morphologies depending on light availability and hydrodynamic energy, with deeper-dwelling species typically having thinner, flatter tests. Shallow-water species tend to have more robust, biconvex tests.

The genus *Lepidocyclina* (Fig. 4B), on the other hand, is extinct. Several species, subspecies and varieties of *Lepidocylina* have been described (Chaproniere, 1984). As with *Amphistegina*, test morphology of lepidocyclinids appears to have been environmentally controlled, with a trend towards larger, flatter tests in deeper-dwelling individuals. *Lepidocyclina* is most common in assemblages typical of oceanic salinities. Chaproniere (1975, 1984) believed that lepidocyclinids occupied a substantial range of depths, although it was not known to thrive in very shallow (i.e., less than ~10 m depth) waters.

A. *Amphistegina* - 1193A 6xcc



B. *Lepidocyclina* with abundant Globigerinid foraminfers - 1193A 5h 1-142



C. *Cycloclypeus* - 1193 A 65x cc

Figure 4 _ Common Larger Benthic Foraminifers from Marion Plateau rocks and sediments. A) *Amphistegina* B) *Lepidopcyclin*a and C) *Cycloclypeus.*

Cycloclypeus is believed to have inhabited a greater range of water depths than it does today (Fig. 4C). In the modern oceans, *Cycloclypeus* is restricted to the deepest part of the euphotic zone (i.e., oligophotic habitats, Chaproniere, 1975). *Cycloclypeus* test morphologies vary with water depth, similarly to *Lepidocylina* and *Amphistegina*. Modern forms tend to have large, flat, thin tests. Extinct forms with more robust, biconvex tests are believed to have lived in somewhat shallower waters (Chaproniere, 1984).

Operculina is another extant genus and was a common LBF taxa in Miocene-aged rocks and sediments (Fig. 5A). It is found in a wide range of environments and is widely distributed (Chaproniere, 1975). It is postulated that *Operculina* prefers lower light intensities and, although this is certainly correlated with water depth, the two parameters are not intimately tied. *Operculina* might have easily been found in shady areas of shallow-water environments such as under reef rubble, or the shade zones of larger organisms (Hohenegger, 1984). *Operculina* also tolerates more turbid conditions and is often the only LBF genus found in some terrigenous facies (Hohenegger, 1999).

Miogypsina is another extinct genus that was common during the Miocene (Fig 5B). Probably restricted to the photic zone by their algal endosymbionts, early miogypsinids are commonly found in sediments that bear hallmarks of the shallowest parts of the photic zone (Drooger, 1993). Drooger (1993) postulates that the protists probably lived on or within the vegetation of carbonate platforms and forereef slopes.

A. *Operculina* - 1193A 6 x cc

B. *Miogypsina* - 1193A 63 x 1-3

C. *Austrotrillina* - 1196A 20 r 1-57

D. *Flosculinella* - 1196A 20 r 1-57

Figure 5 - Common Larger Benthic Foraminifers from Marion Plateau rocks and sediments. A) *Operculina* B) *Miogypsina* C) *Austrotrillina* and D) *Flosculinella*.

Some species and varieties of *Miogypsina* were adapted to deeper water conditions, with longer, flatter, thinner tests than their shallow-water counterparts (Drooger, 1993).

Austrotrillina (Fig. 5C) and *Flosculinella* (Fig. 5D) are two LBF taxa that are quite different from those previously mentioned. Firstly, their tests are composed of porcellaneous, as opposed to hyaline, calcite, and secondly, they lived in much shallower water than the majority of the other taxa previously mentioned. Both genera are now extinct. *Austrotrillina* was probably restricted to shallow, meta-haline waters (Chaproniere, 1975), as are many of the modern miliolid foraminifers. *Flosculinella* was also restricted to shallow, meta-haline waters, and is believed to have been analogous to modern-day alveolinids (Chaproniere, 1975).

Project Objectives

Qualitative analysis of benthic foraminiferal assemblages revealed four major LBF assemblages, which appear sequentially and are thought to record temporal stages in platform development on the Marion Plateau (Hallock *et al.,* submitted). The first assemblage (A) is associated with the basement flooding sequence on the northern highstand and southern platforms and is dominated by *Lepidocyclina*. Assemblage B, characterized by *Lepidocyclina* as well as abundant *Amphistegina* and *Operculina*, is found in platform facies on the northern highstand and southern platforms. The third

assemblage (C) was found only on the southern platform, and is characterized by *Flosculinella, Austrotrillina,* and smaller soritid and miliolid foraminifers. The final assemblage (D) was also found only in the platform facies recovered from the southern platform and is dominated by *Amphistegina,* with common *Lepidocyclina*. The four assemblages described above are postulated to represent different intervals of platform development: Early Miocene (A), Late Early to Middle Miocene (B), Middle Miocene (C), and Late Miocene (D) (Hallock *et. al.,* submitted).

My project will utilize quantitative methodologies to describe and document the sediment constituents preserved on the northern highstand platform (Site 1193), the northern lowstand platform (site 1194) and the southern platform (Site 1196) during the Miocene Epoch. The presence, absence, abundance and proportions of sediment constituents will be used to make interpretations about environmental conditions at the time of their deposition. The results of quantitative analyses will be compared to the qualitative interpretations of these sediments described above. It is hoped that the quantitative techniques used in this project will elucidate answers to two fundamental questions still unanswered by Leg 194 post-cruise work: 1) why are the depositional histories of the northern and southern platforms so different, and 2) is the assumption of in-situ deposition on the lowstand ramp site (site 1194) correct?

Accurate paleoenvironmental and paleowater-depth interpretations for the second-order highstand platform complex and the adjacent second-order lowstand ramp complex on the Northern Marion Plateau are critical for constraining the late-Middle Miocene eustatic sea-level fall. This is because the potential for error in the sea-level calculation

(as described previously, Shipboard Scientific Party, 2002) comes primarily from the paleowater-depth ranges as estimated by qualitative benthic foraminiferal-assemblage assessment in the appropriate intervals in cores from sites 1193 and 1194. Paleoenvironmental and paleowater-depth interpretations for the platform complex on the Southern Marion Plateau is critical to understanding of environmental, ecological and oceanographic processes interacting during the Miocene on the Marion Plateau.

Methods

The data source for this project was 142 thin sections cut from platform sediments from sites 1193, 1194 and 1196. Specifically, thin sections from the Middle and Late Miocene sequences: Lithologic Units IIIA and B from Site 1193 (Fig. 2); Lithologic Unit IIIA from Site 1194 (Fig. 2) and Lithologic Units IA-D and II A and B from Site 1196 (Fig. 3) were analyzed (lithologic units as defined by Shipboard Scientific Party, 2002). Because of low recovery, samples investigated from different holes drilled at each site were combined and considered together, based on depth in the core below the sea floor.

Eight high-quality digital photomicrographs were taken of each thin section, at varying resolutions, suitable for capturing the greatest amount of sedimentological information (the magnification was, with few exceptions, 16x). The image files were imported into a digital point-count program, PointCount '99 (Dustan, 1999), which was customized for use in this project. On each photomicrograph, 25 random points were counted for a total of 200 points per thin section.

The thin sections were examined quantitatively for major sedimentological constituents, including 13 distinctive foraminiferal groups: alveolinids, *Austrotrillina*, *Flosculinella,* soritids, other miliolids, *Amphistegina, Cycloclypeus, Lepidocyclina,*

Miogypsina, Operculina, small rotalids, globigernids and globorotalids. Sediment constituents counted include bryozoans, bivalves, corals, echinoderms, cements, rhodoliths, red algal fragments, rhodoliths, void space and both sand- and mud-sized grains composing the matrix. Where identifiable, void space was categorized as either primary or secondary porosity. This was not always possible within one micrograph, however. The terminology "sand-sized matrix", as used in this project, described sand-sized carbonate particles that are otherwise unidentifiable, that is to say, this term refers to a size-class of sediments that cannot otherwise be identified as to their origin.

Analyses followed two courses: first, an analysis of all sediment constituents, and second, the analysis of foraminiferal taxa alone. Numerical analyses of foraminiferal assemblages followed multivariate data-analysis methods outlined by Hallock and Glenn (1985, 1986), including R-mode and Q-mode Cluster Analysis, and Principle Components Analysis (PCA).

Cluster analysis is the most commonly used multivariate statistical technique in the foraminiferal literature (Parker and Arnold, 1999). It is especially powerful in delineating biofacies and species associations, although it is an exploratory technique, which must be backed up with further analyses. In this case, Principal Components Analysis and Multi-Dimensional Scaling (Dillon and Goldstein, 1984) were chosen to confirm the results of the cluster analyses. These analyses were conducted using PRIMER (Plymouth Routines In Multivariate Ecology, v5; Clarke and Gorley, 2001; Clarke and Warwick, 2001).

Point count data were tabulated for each of the sites separately and for all of the sites together. The data were square root-transformed and the similarities both among samples (Q-mode cluster analysis) and among sediment constituents (R- mode cluster analysis) were computed using a Bray-Curtis similarity coefficient (Parker and Arnold, 1999; Clarke and Warwick, 2001). Rare taxa (i.e., comprising less than 1% of all sediment constituents in a given set of samples) and highly recrystallized samples were removed from the analyses. The rare taxa removed from the analyses of each site were, of course, therefore different, depending on the abundances of various sediment constituents in those samples. The resultant similarity matrices were plotted as dendrograms (clusters) and in multidimensional space (MDS). PCA was performed only on the data combined from all three of the sites.

Paleoenvironmentally representative LBF taxa, as revealed by the cluster analysis, were chosen to aid in paleoenvironmental interpretation. The proportions of these taxa, with respect to the other relevant groups in each sample, were plotted versus depth. Paleoenvironmental interpretations were made by comparing benthic foraminiferal assemblage data with existing models (e.g., Chaproniere, 1975, 1983; Hallock and Glenn, 1985, 1986; Betzler and Chaproniere, 1993; Hottinger, 1997; Hallock, 1999; Hohenegger, 1999, 2000, 2004). Specific assemblages were then identified by the abundances of these functional-group taxa in each sample, when considered in relation to lithological and sedimentological information gleaned from point counts.

Results

Northern Highstand Platform

Sediments recovered from the northern highstand platform drilled at Site 1193 were classified into seven lithostratigraphic units (I-VII) during shipboard analysis (Shipboard Scientific Party, 2002). Of these seven units, only units IIIA, IIIB, and VI will be discussed in this paper, as preliminary analysis determined that these units represent periods of platform deposition at this site (Shipboard Scientific Party, 2002). The other units contain hemipelagic sediments or too few benthic foraminifers to be useful in this paleoenvironmental analysis.

Unit VI (390.25-522 mbsf) grades from mixed carbonate-siliciclastic to a fully carbonate unit, representing a period of mixed deposition on the plateau (Shipboard Scientific Party, 2002). The dominant fabric of this unit is bryozoan and foraminiferal skeletal debris in a sand-sized matrix. Benthic foraminifers were uncommon in the deepest parts of this unit. When benthic foraminifers were present, primarily in the upper part of the unit, *Lepidocyclina* was the most common taxon found, with occasional *Amphistegina*. The lower part of the unit contained an abundance of glauconitic grains,

as well as a great deal of siliciclastic material, and very few benthic foraminifers. A great deal of recrystallization had taken place, and LBF molds were present but taxa were not identifiable from these molds.

Unit III 36.65-222.89 mbsf) was split into two subunits, IIIA (36.65-157.80 mbsf) and IIIB (169.54-222.89 mbsf) by the Shipboard Scientific Party (2002). The first of these, Subunit IIIB, is a *Lepidocylina -Amphistegina* rich grainstone, with abundant bryozoans and *Operculina*. Subunit IIIA is also a bryozoan-rich grainstone unit in which *Amphistegina* and *Lepidocyclina* are common, although these have thinner tests than in the previous subunit. Large, flat *Cycloclypeus* and occasional *Miogypsina* are also found in this interval.

Q-mode cluster analysis of samples from Site 1193 split the samples into seven sub-groupings, with some outliers (Fig. 6). Samples from the same lithologic units did not necessarily plot with other samples from that unit. MDS representation of Q-mode similarity analysis (Stress = 0.21) also split the Q-mode similarity data into several small groups, with several outliers (Fig. 7). The high level of stress in this MDS plot makes it an unreliable document from which to draw conclusions; therefore categorization of clusters is based solely upon the dendrogram.

Cluster 1 (Fig. 6) consists of five siliciclastic and mud-rich samples and clustered at ~30% similarity. Bryozoans are rare in these samples, as is (as compared to the remaining samples) porosity. Very few LBF taxa are present, with *Cycloclypeus* the most common.

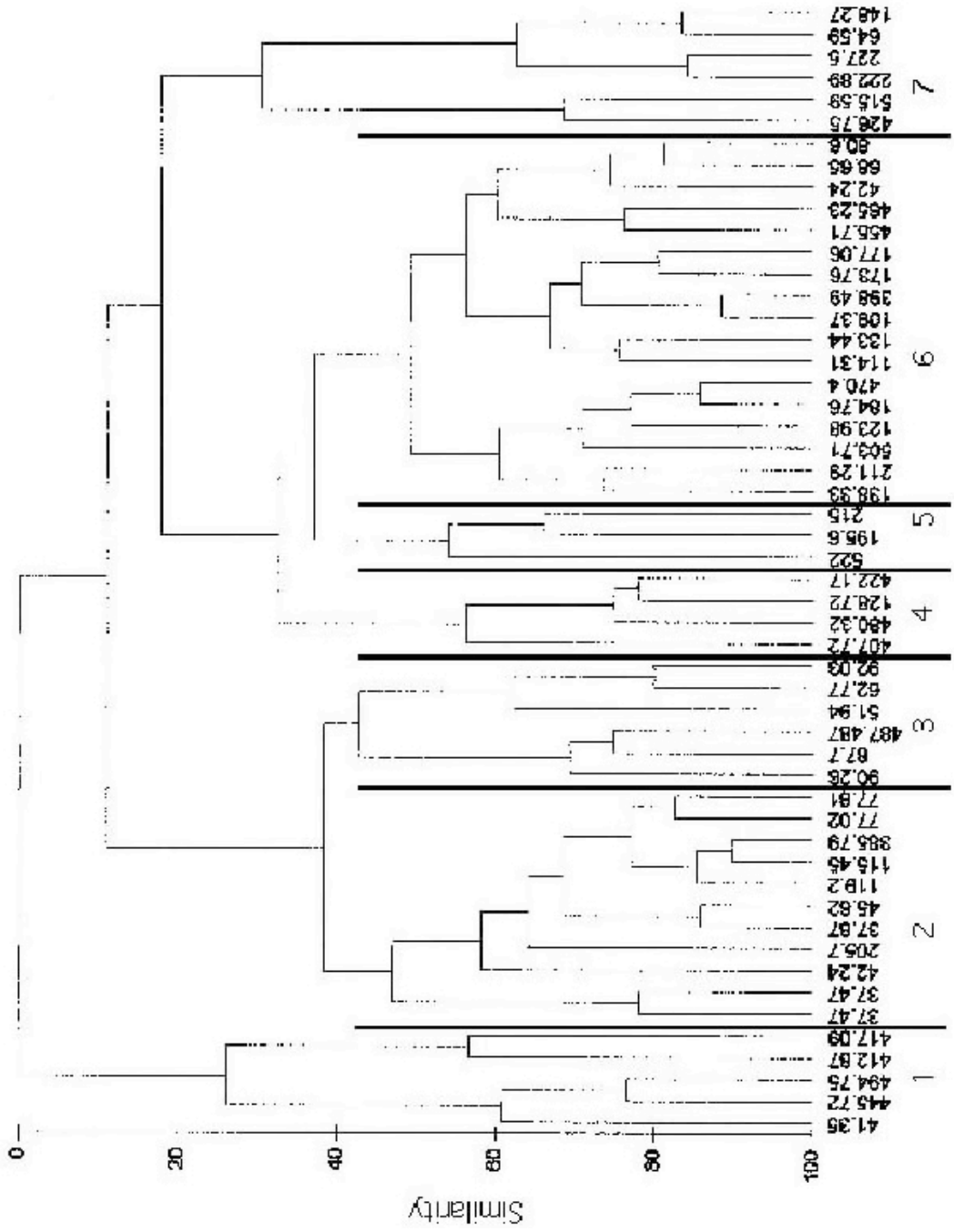


Figure 6 - Q-mode cluster analysis of northern highstand platform (Site 1193) sediment data.

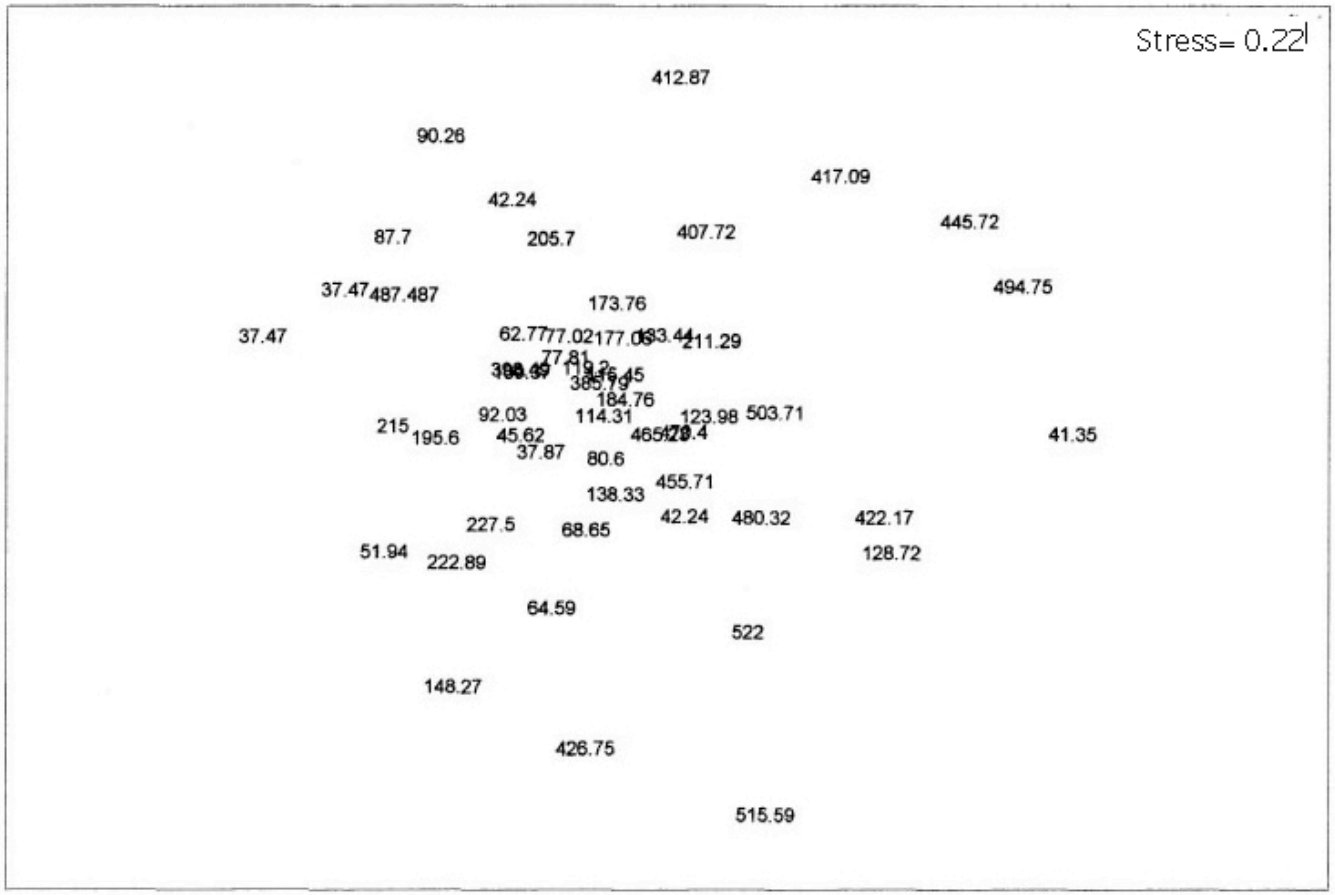


Figure 7 – Q-mode MDS plot of northern high stand platform (Site 1193) sediment data. Stress value of 0.22 indicates relatively poor representation of the data.

Planktonic foraminifers, primarily globigerinids, are also found in these samples. The presence of planktonic foraminifers suggest a pelagic influence on these samples. It is odd, however, that bryozoans are rare in these samples: bryozoans are not photosynthetic, and therefore do not require light to thrive. Possibly, these samples indicate times of increased siltation, to levels at which bryozoans, being filter feeders, were excluded.

Cluster 2 (Fig. 6) represents the most coral-rich samples, and which clustered at ~50% similarity. Siliciclastic grains are absent in these samples and mud is rare. Instead, sand-sized matrix is more common. The most common LBF taxa in these samples are *Amphistegina* and *Lepidocyclina*. These trends suggest a moderately shallow depositional environment, with little to no fluvial input. There is a great deal of porosity and cement in these samples, indicating some post-depositional dissolution and recrystallization.

The constituents that are dominant in cluster 3 (Fig. 6) were quite similar to those that compose cluster 2. The difference between these two groups is that there is much more mud in the samples that comprise cluster 3 than in cluster 2. These samples are also dominated by bryozoans, *Amphistegina* and *Lepidocyclina,* and there are fewer corals in these samples. This grouping is interpreted to represent a deeper euphotic environment than that interpreted for cluster 2. The samples in this group clustered together at a similarity of ~40%.

Cluster 4 (Fig. 6) consists of a group of recrystallized samples: the vast majority of points counted in these samples were ‘sand-sized matrix’, a catchall term for unidentifiable sand-sized grains. LBF taxa, when present, were most commonly

Amphistegina and *Lepidocylina*. Bryozoans were rare in most of these samples. Samples in this group clustered together at ~60% similarity.

Cluster 5 (Fig. 6) is an interesting group: it is comprised of samples with the most diverse assemblage of all of the samples from Site 1193. The most common foraminifer in these well-cemented samples is *Lepidocyclina*, although small miliolids also occur. These samples clustered at ≥55% similarity.

Cluster 6 (Fig. 6) is the biggest grouping of samples in the dendrogram; these samples were at least 35% similar. *Amphistegina*, *Lepidocyclina* and abundant bryozoans characterize these samples. *Operculina* is also common in several of these samples. The presence of *Operculina* suggests a somewhat deeper water influence than in the other clusters, although not as deep as in Cluster 1. Two sub-clusters can be differentiated primarily based upon the abundance of *Miogypsina* present in these samples. One sub-cluster contains abundant *Miogypsina,* while the other does not contain as many: these are mostly the ovate form of *Miogypsina*.

Cluster 7 is comprised of samples completely dominated by bryozoans, to the exclusion of most other sediment constituents. There are no *Amphistegina* in these samples. *Lepidocyclina* and *Cycloclypeus* are rare, when they do occur. This group clustered at ~30% similarity, although samples within the group clustered at as much as ~80% similarity.

R-mode cluster analysis of sediment constituents revealed several interesting groupings (Fig. 8). The tightest biotic cluster is comprised of *Amphistegina* and *Lepidocyclina*, which clustered together at nearly 60% similarity. These common

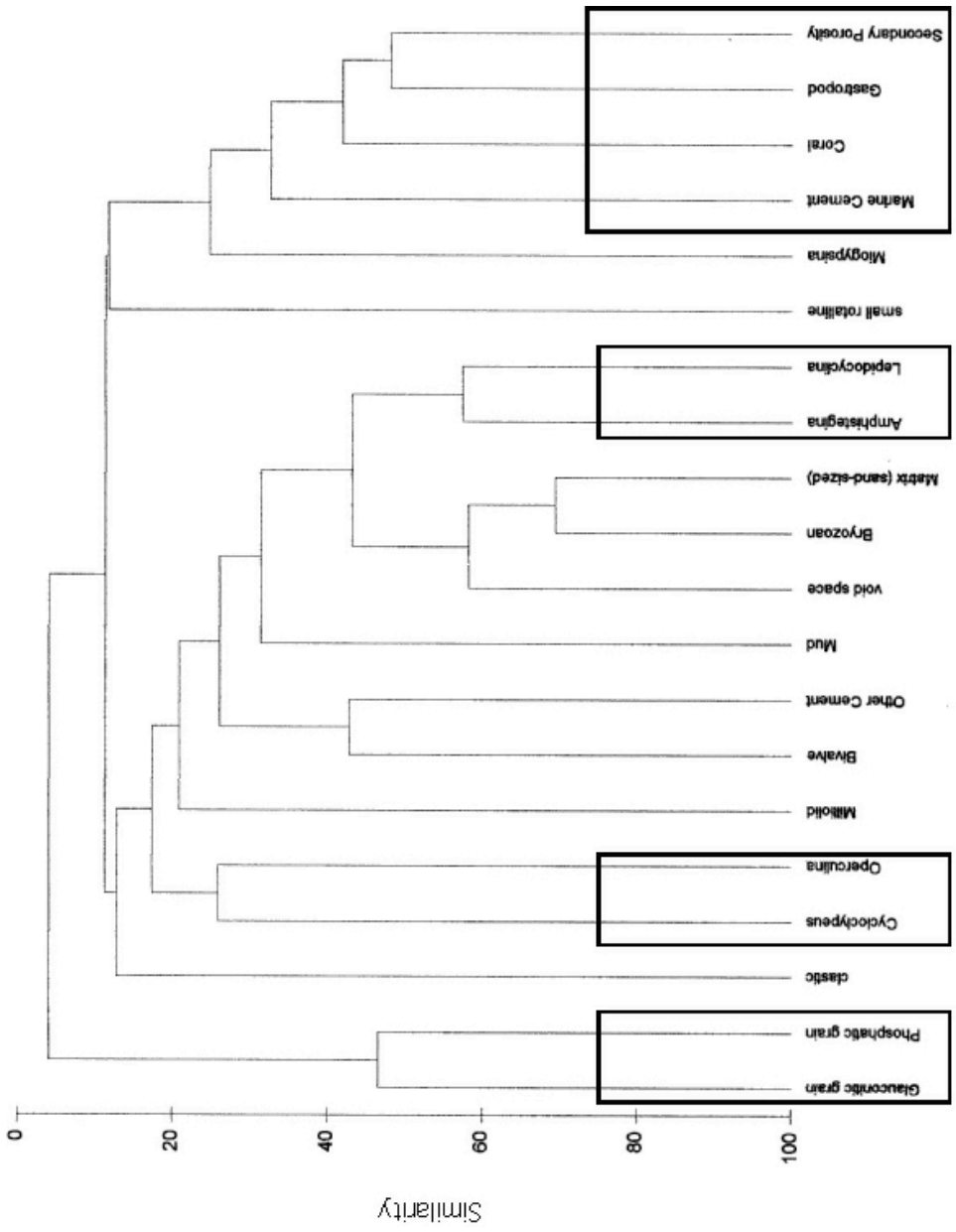


Figure 8 - R-mode cluster analysis of northern highstand platform (Site 1193) sediment constituent data. Interpretations made on figure are explained in the text.

foraminifers clustered most strongly with bryozoans, void space and sand-sized matrix, the most common sediment constituents at Site 1193. Gastropods, corals, cements and identifiable porosity (both primary and secondary porosity) clustered together at ≥30 % similarity. This cluster is likely due to the higher dissolution potential of these aragonitic grains. *Cycloclypeus* and *Operculina*, foraminifers adapted to oligophotic conditions, clustered together at ~30% similarity. Glauconitic grains and phosphatic grains clustered together at ~50% similarity and were the outliers of the dendrogram. Planktonic foraminifers were removed from this analysis, as they were exceedingly rare in the samples studied.

MDS representation of R-mode similarity data (stress=0.12) groups the sediment constituents into three associations (Fig. 9). The first, and most commonly found at Site 1193, consists of bryozoans, sand-sized matrix, void space, *Lepidocyclina*, *Amphistegina*, mud, bivalves and other cements (mostly dolomite). This association is interpreted as representing deposition in an open-platform setting at depths of less than 50 m. The second association is of the aragonitic skeletal components along with secondary porosity. The final association is comprised of *Cycloclypeus*, *Operculina*. This association represents deposition in deeper environments, consistent with a deep, open-shelf or reef-slope environment. Finally, siliciclastic, phosphatic and glauconitic grains all plotted as outliers on the MDS plot.

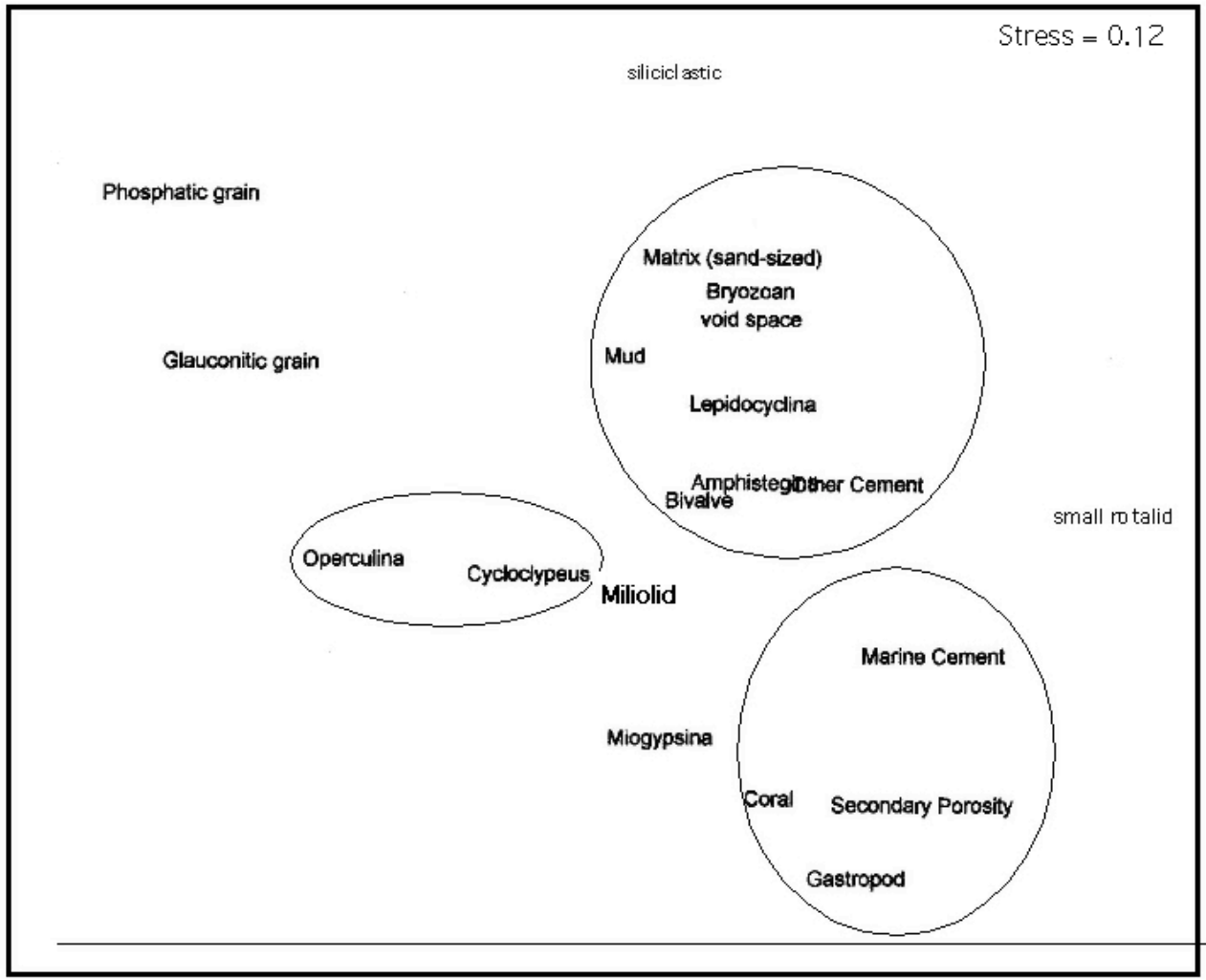


Figure 9 – R-mode MDS plot of northern highstand platform (Site 1193) sediment constituent data. Stress value of 0.12 indicates a reliable representation of the data.

R-mode cluster analysis including only foraminiferal taxa revealed two main clusters (Fig.10). *Lepidocyclina* and *Amphistegina* were found together more than 60% of the time. These were the most common foraminiferal taxa found in sediments from Site 1193, and weakly clustered with *Cycloclypeus* at ~ 30% similarity. Miliolid foraminifers were an outlier to this group, clustering at approximately 20% similarity with *Cycloclypeus, Amphistegina* and *Lepidocylina*. This cluster is interpreted to represent deposition in an open, euphotic to oligophotic environment. *Miogypsina* and *Operculina* clustered loosely at ≥20% similarity. Globigerinid and globorotalid planktonic foraminifers clustered together at a similarity of ≥40%.

MDS representation of R-mode similarity of foraminiferal taxa alone confirms the cluster analysis, with a few differences (Stress =0.04; Fig. 11). Interpretation of the MDS data shows a depth trend in the foraminiferal data, which can further be broken down into two sub-components. The left side of the figure represents shallow, euphotic conditions, and the right side represent relatively deeper, oligophotic to pelagic conditions. It is interesting to note that *Lepidocyclina* and *Amphistegina* are not the two closest taxa in the MDS representation. In fact, *Cycloclypeus* is plotted relatively closer to both *Lepidocyclina* and *Amphistegina* than they are to each other.

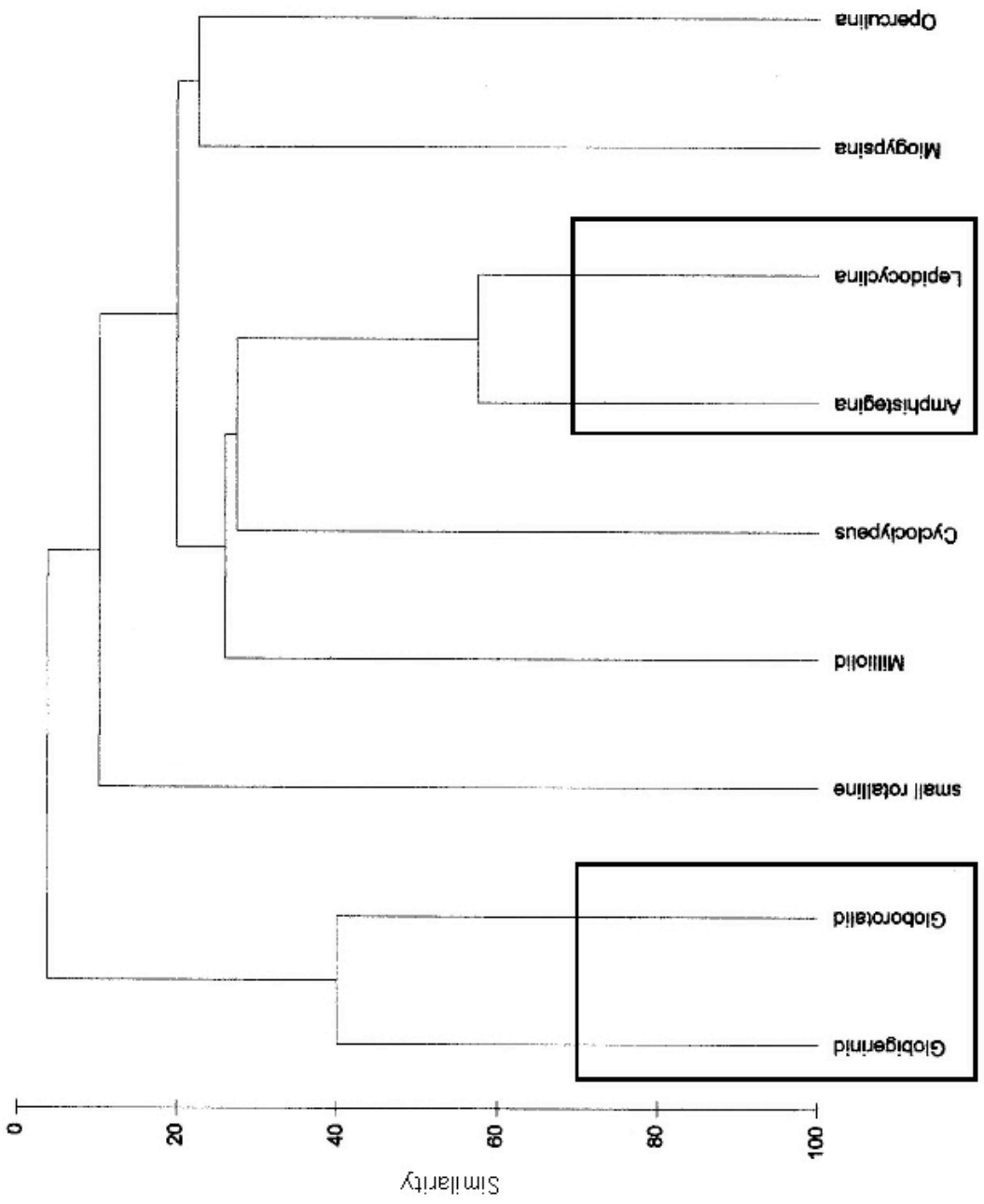


Figure 10 – R-mode cluster analysis of northern highstand platform foraminiferal taxa.

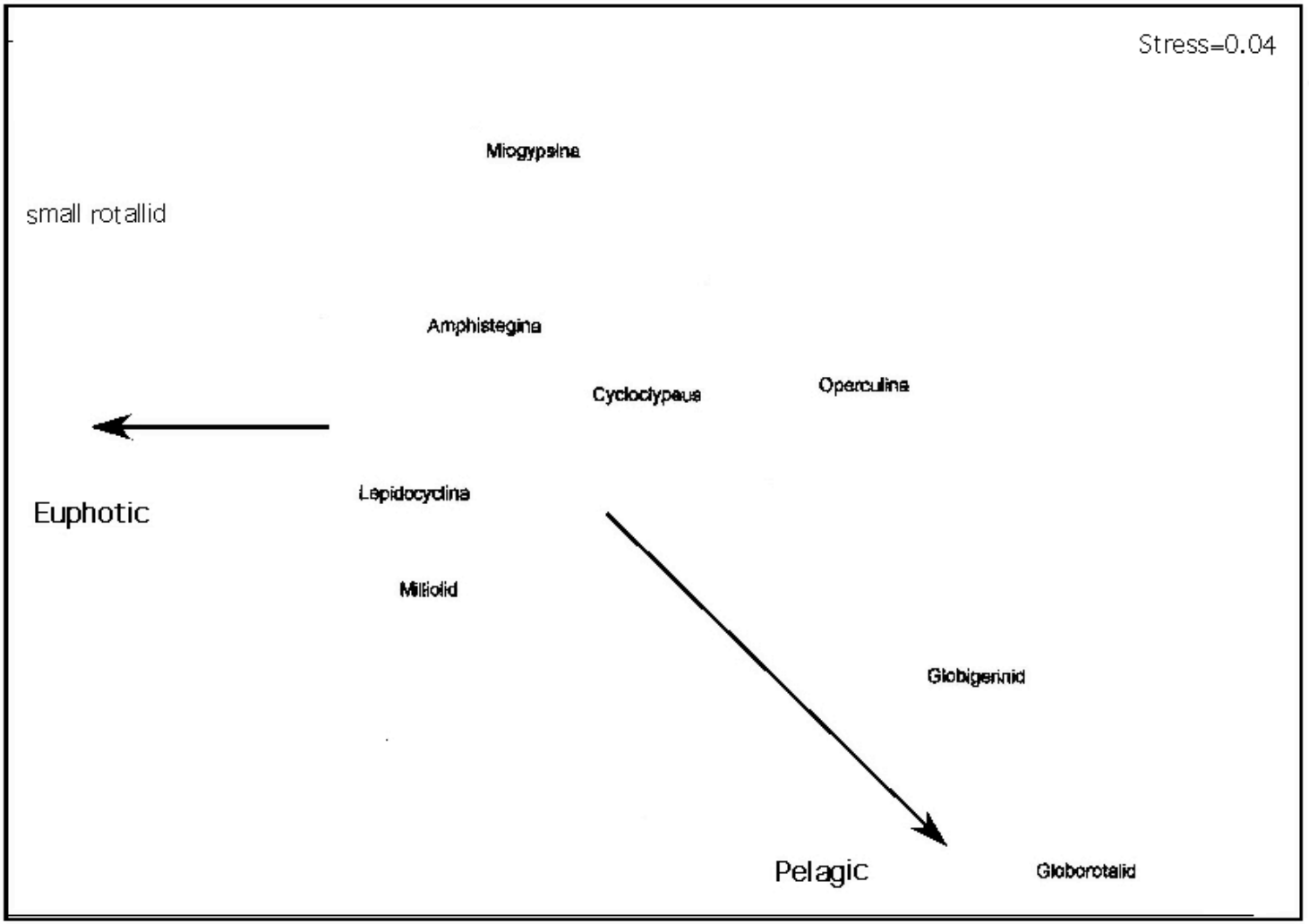


Figure 11 – R-mode MDS plot of foraminiferal taxa from the northern high stand platform (Site 1193). Stress value of 0.04 indicates an excellent representation of data. Interpretations made on the figure are explained in the text.

Northern Lowstand Ramp

Only samples from the hypothesized low-stand ramp deposit at Site 1194 were analyzed for this study. These samples all came from lithologic Unit III, from 115 to 158 mbsf (Shipboard Scientific Party, 2002). Unit III is a mud-rich unit, with several intervals of bryozoan-rich skeletal grainstones and floatstones. The most prevalent LBF taxa included *Amphistegina, Lepidocyclina* and *Operculina*. Several samples contained abundant planktonic foraminifers, as well as sparse representatives of the LBF taxa above and some bryozoan fragments.

Q-mode cluster analysis revealed two major groupings of samples (Fig. 12). All samples in Group 1 are from less than 150 mbsf, while five of the seven samples in Groups 2 were from deeper than 150 mbsf. Group 1 occurs in a fine-grained interval, with common bryozoans and planktonic foraminifers. The most abundant LBF taxon in this interval is the oligophotic *Operculina*. This interval is interpreted as having been deposited in a low-light, deep-ramp environment. Group 2 from deeper in the core, occurs in a sandier interval, with abundant bryozoans, *Amphistegina* and other small miliolids. MDS representation of the Q-mode similarity data (Fig. 13) segregated the samples into two major clusters (Stress = 0.08).

R-mode cluster analysis of all sediment constituents revealed four groupings at ≥50% similarity (Fig. 14). *Amphistegina* and other miliolids grouped together at ≥75%

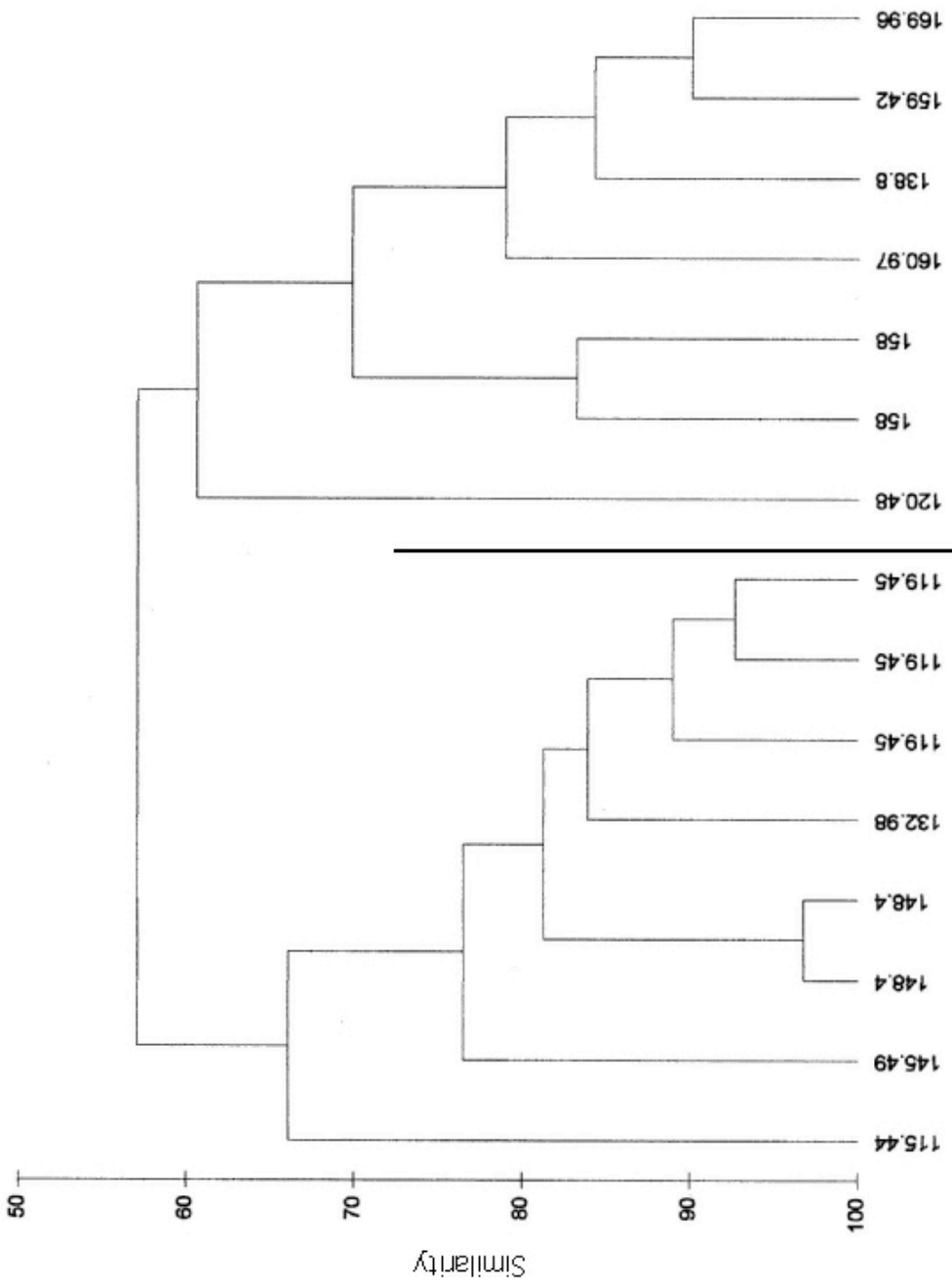


Figure 12 - Q-mode cluster analysis of northern lowstand ramp (Site 1194) sediment data. Cluster numbers are explained in text.

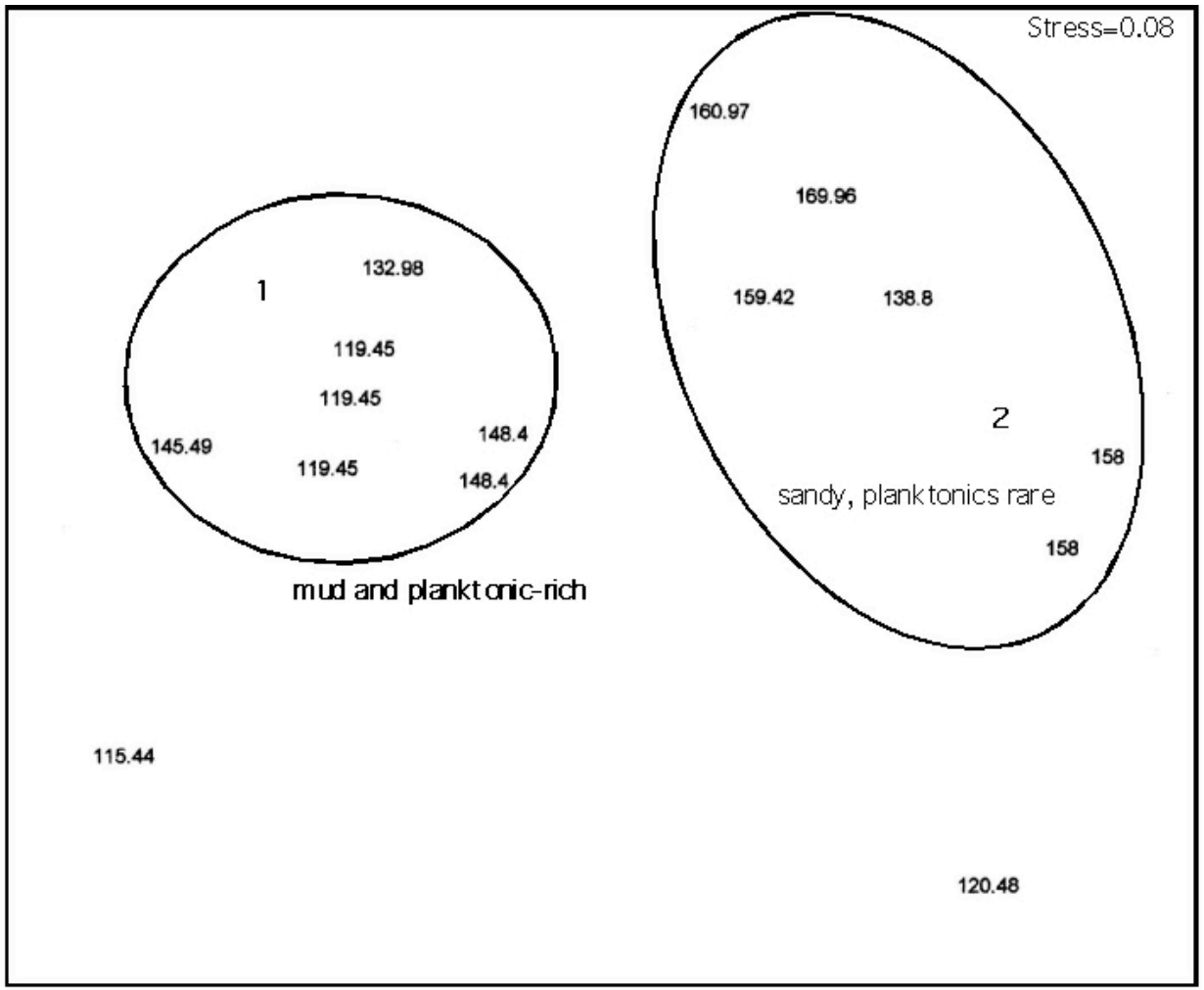


Figure 13 – Q-mode MDS plot of Northern lowstand ramp (Site 1194) sediment data. Stress value of 0.08 indicates excellent representation of the data. Interpretations are noted in the figure.

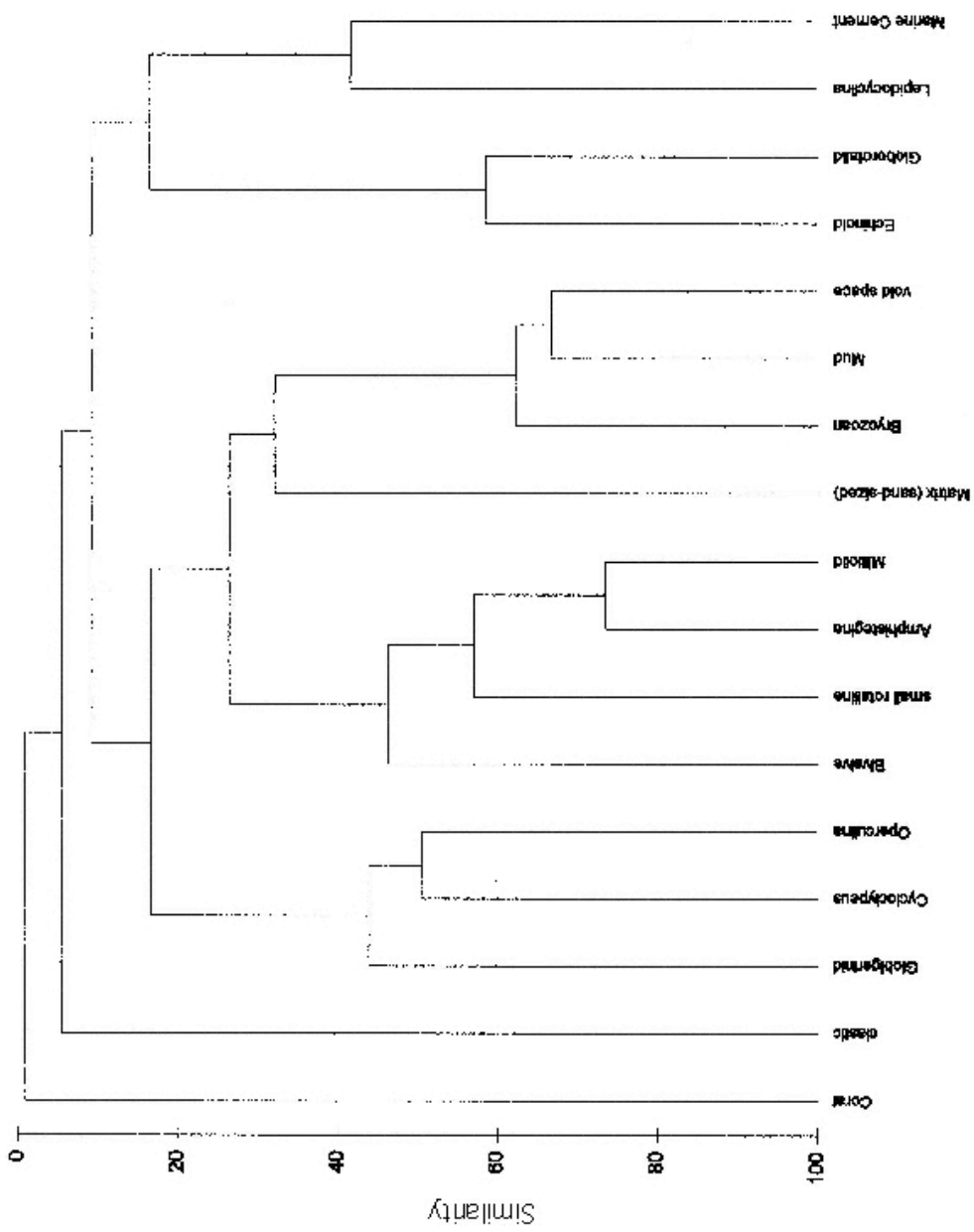


Figure 14- R-mode cluster analysis of northern lowstand ramp (Site 1194) sediment constituent data.

similarity, and these two clustered with small rotaliids at ≥55%. This indicates either a shallow-water assemblage influence at Site 1194, or intervals of increased sediment transport from the northern highstand platform. *Cycloclypeus* and *Operculina* clustered together at ≥50 % similarity, and more distantly with globigerinid foraminifers. This cluster can be interpreted to be representative of times of oligophotic zone production and deposition at Site 1194, or as subeuphotic deposition with input from upslope oligophotic habitats. The two remaining groupings contained bryozoans with mud and void space, and globorotalids with echinoid fragments.

MDS representation of the R-mode similarity (Fig. 15) showed a closer similarity between *Amphistegina* and *Lepidocyclina* than in the dendrogram (Stress= 0.12). The same two assemblage types are represented in the MDS plot: the shallow-water, euphotic cluster consisting of *Amphistegina*, *Lepidocyclina*, miliolids, small rotaliids and sand-sized matrix (along with some other rare constituents), and the oligophotic cluster consisting of *Cycloclypeus*, *Operculina* and globigerinid foraminifers.

R-mode cluster analysis of foraminiferal taxa alone revealed two major groupings as well (Fig. 16). The first grouping was comprised of *Lepidocyclina, Amphistegina*, small rotaliids and other miliolids, an assemblage that is interpreted to represent a strong shallow-water influence on deposition on the lowstand ramp. The second grouping included *Cycloclypeus* and *Operculina* as well as globigerinid foraminifers, and more distantly, globorotalid foraminifers. As noted previously, *Cycloclypeus* and *Operculina* thrive in quiet, low-light, deep-water environments. MDS representation of this similarity (Stress = 0.01) confirmed these groupings (Fig. 17).

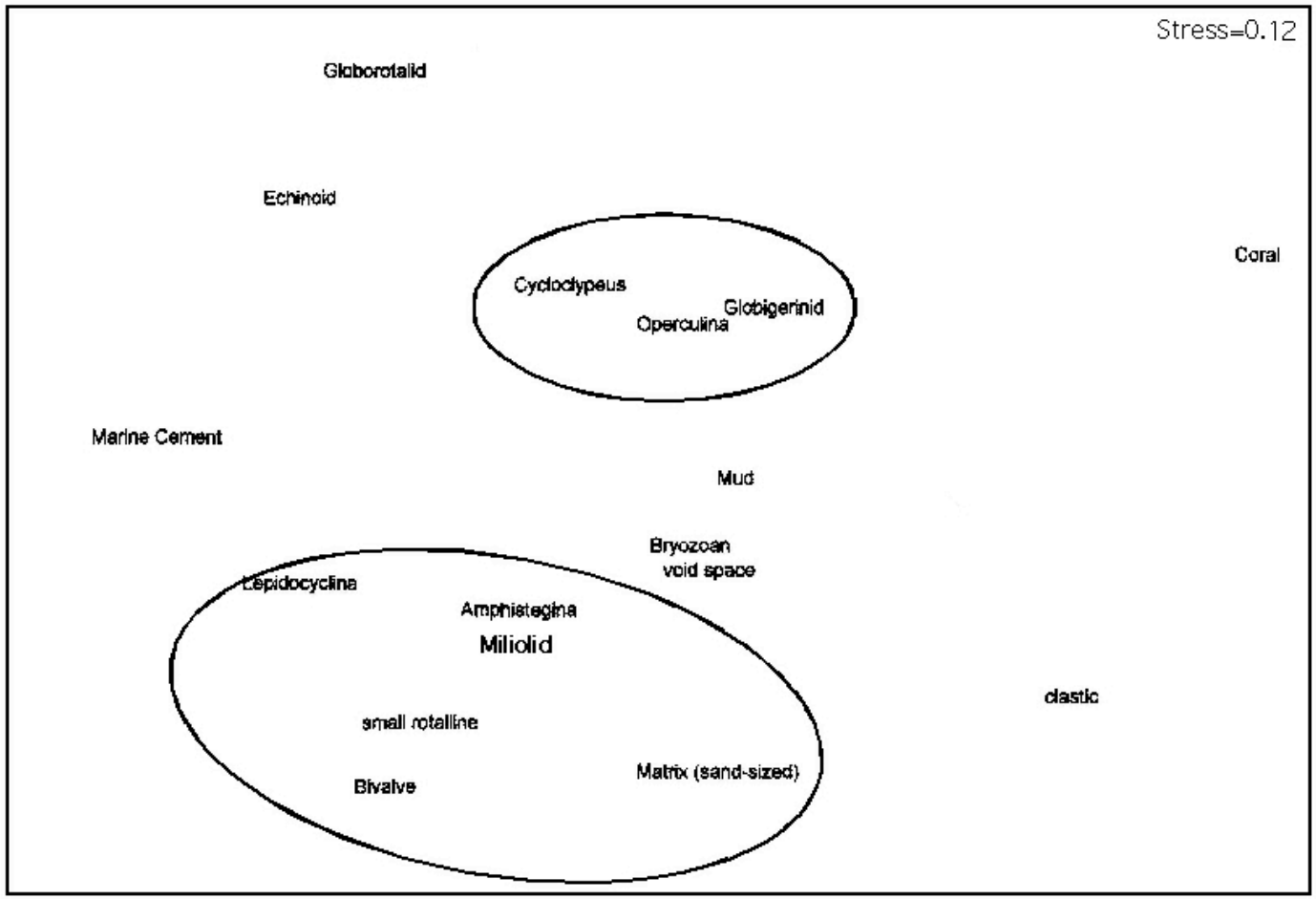


Figure 15- R-mode MDS plot of northern lowstand ramp (Site 1194) constituent data. Stress value of 0.12 indicates a reliable representation of the data. Interpretations noted on figure are explained in the text.

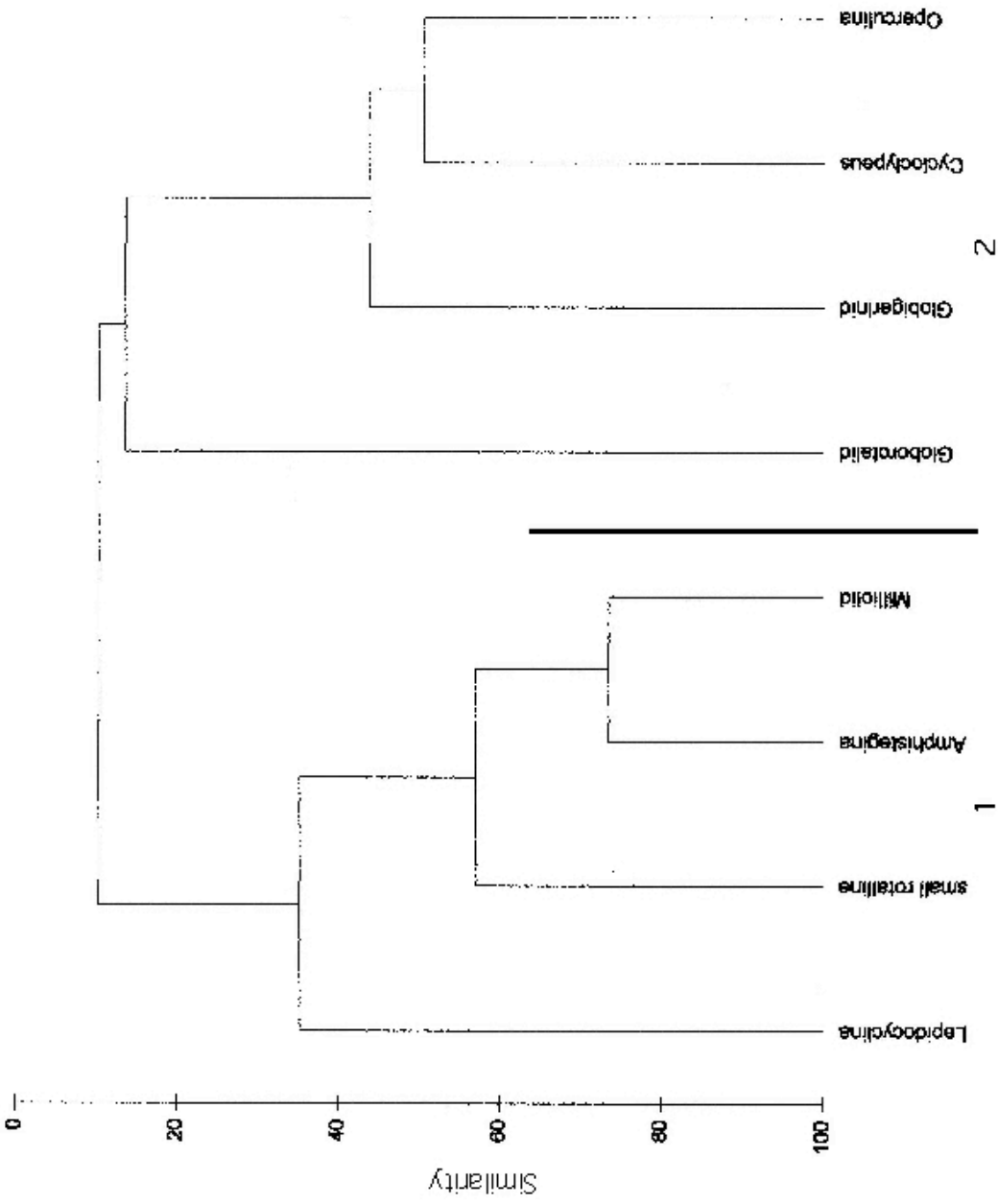


Figure 16 – R-mode cluster analysis of northern lowstand ramp foraminifers. Cluster numbers are explained in the text.

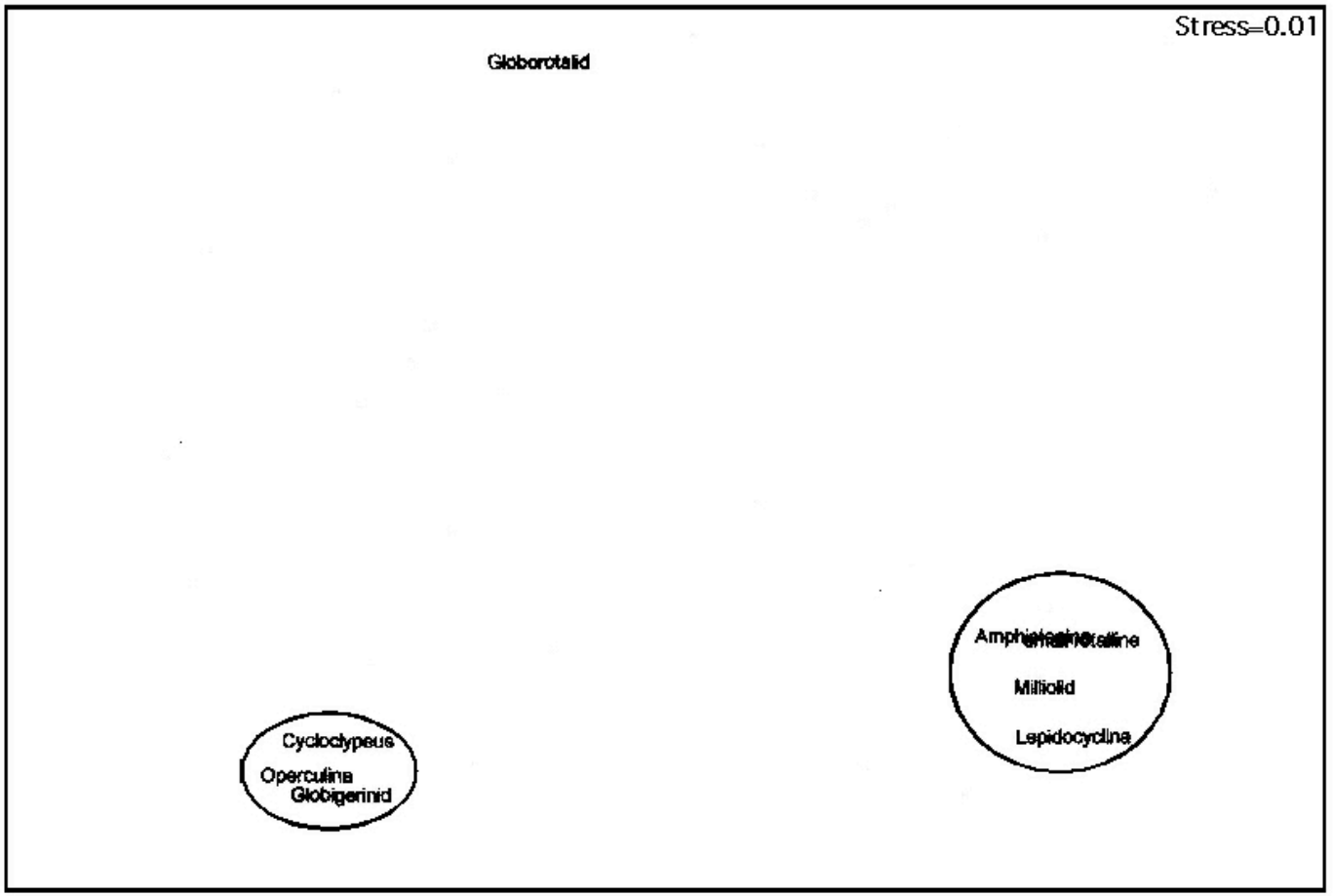


Figure 17 – R-mode MDS showing distinct separation of foraminiferal groups at Site 1194, the northern lowstand platform. Stress value of 0.01 indicates an excellent representation of the data.

Southern Platform

Sediments recovered from the southern platform consist of well-lithified, shallow-water carbonates representing a significant carbonate edifice (the southern platform complex), which overlies a siliciclastic substrate (Shipboard Scientific Party, 2002). Rocks and sediments recovered from Site 1196 are dominated by coralline red algae. The carbonate sediment succession was subdivided into four lithologic units on the basis of carbonate mineralogy and the nature of the sedimentary constituents (Shipboard Scientific Party, 2002). Some of the lithologic units identified from Site 1196 (Units IIB –V) were highly recrystallized making sediment-constituent identifications impossible (Shipboard Scientific Party, 2002). These units were not considered in this project.

Lithologic Unit 1 (0-180 mbsf) was subdivided into 4 subunits based on biotic assemblage (Shipboard Scientific Party 2002). Subunits IA, IB, and ID are mostly dolomitic in composition, whereas Subunit IC is predominantly calcitic.

Subunit IA (0 - ~ 120 mbsf) consists of dolomitic floatstone/rudstone characterized by the occurrence of centimeter-sized rhodoliths and coral fragments in a grainstone matrix (Shipboard Scientific Party, 2002). This matrix contains *Amphistegina* and *Miogypsina,* red algae, mollusks, and rare bryozoan fragments. The dolomitization of this unit is not pervasive and skeletal components are still readily identifiable. Both primary and secondary porosity is common in these samples.

Subunit IB (~120 -~126 mbsf) consists of light brown, well lithified, dolomitized skeletal floatstone with a recrystallized grainstone matrix (Shipboard Scientific Party, 2002). The skeletal components common in this interval include elongated fragments of branching coralline algae and mollusks. Numerous molds of flat, larger benthic foraminifers also occur, but were not further identifiable. Dolomitization is more pervasive than in Subunit IA, but the original texture of the rock is still visible in most intervals.

Subunit IC (~ 130 - ~ 150 mbsf) was very poorly recovered (Shipboard Scientific Party, 2002). Recovered sediments from this poorly lithified unit are characterized by skeletal rudstones, floatstones, and boundstones rich in corals, mollusk shell fragments, and rhodoliths (Shipboard Scientific Party, 2002). Coralline algae, *Amphistegina* and *Lepidocyclina* are common in the finer-grained matrix. Both primary and secondary porosity is common throughout this interval, which, unlike overlying units, is essentially composed of calcium carbonate.

Subunit ID (~ 150 – 181 mbsf) is mostly composed of pale brown to brown dolomitic floatstone with a grainstone matrix (Shipboard Scientific Party, 2002). Main constituents include whitish, elongated fragments of branching coralline algae; small rhodoliths; and mollusk shells or molds. LBF occur primarily as molds. Within this subunit, the grainstone matrix is pervasively dolomitized with moldic porosity.

Lithologic Unit IIA (182-336 mbsf) is significantly different from any other sedimentary unit drilled on either of the Marion Plateau's carbonate platforms. In this interval, large and small porcellaneous foraminifers, especially *Flosculinella* and

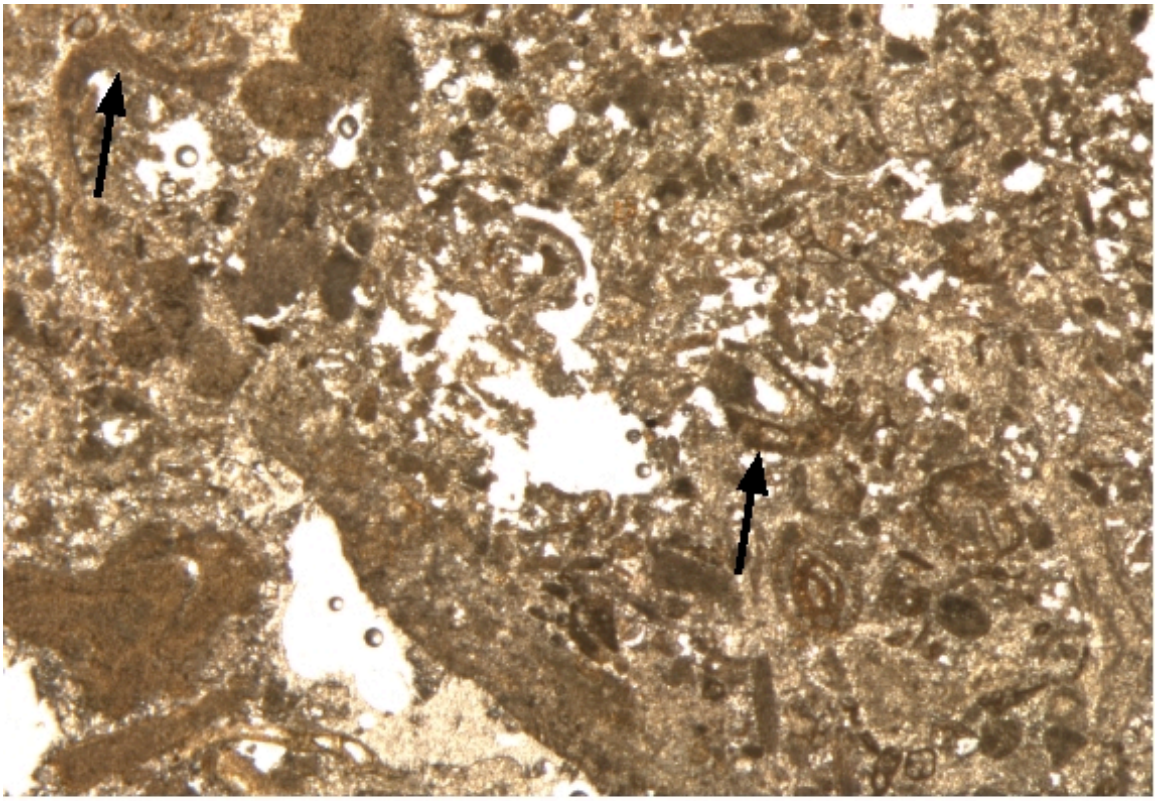


Figure 18 - Digital photomicrograph taken from sample ODP 194- 1196 A 33 2-72, Lithologic Subunit IIA. Arrows indicate the hooked algal morphology that is diagnostic of epiphytic red algae living on macrophytes, such as sea-grasses.

Austrotrillina, and also including smaller miliolids, soritids and alveolinids, dominate the assemblage. Gastropod and bivalve shells and shell fragments are also abundant in this interval of skeletal floatstones and grainstones. Several examples of a hooked epiphytic morphology of coralline red algae are found in the sediments of this interval (Fig. 18).

Q-mode cluster analysis separated the samples in three clusters (Fig. 19). The first cluster is composed primarily of samples from lithologic subunit IIA, these are characterized by an abundance of porcellaneous foraminifers, as well as bivalves and gastropods in a predominantly mud-sized matrix. These samples clustered together at ~60% similarity, with a couple of outliers. The second cluster is composed of particularly coral-rich samples, which tend to also contain *Amphistegina* and *Operculina,* as well as coralline red algae. These samples are interpreted to represent deposition in conditions similar to those found in modern-day coral reefs. The third cluster is composed of samples that are dominated by coralline red algae. These samples are often fairly recrystallized. Rhodoliths are common in these samples. MDS representation of Q-mode similarity does not show a great deal of distance among these groups (Fig. 20), however, despite the removal of coralline red algae from the analysis, which was so dominant in the samples (Stress= 0.2).

R-mode cluster analysis including all sediment constituents revealed four distinct clusters (Fig. 21). The first cluster is composed of *Cycloclypeus* and *Miogypsina*, which clustered together at ≥30% similarity. This cluster is interpreted as representing deposition in a relatively deep, quiet, oligophotic setting. Cluster 2 is composed of rhodoliths, mud, sand-sized matrix, red algae and void space (porosity). These

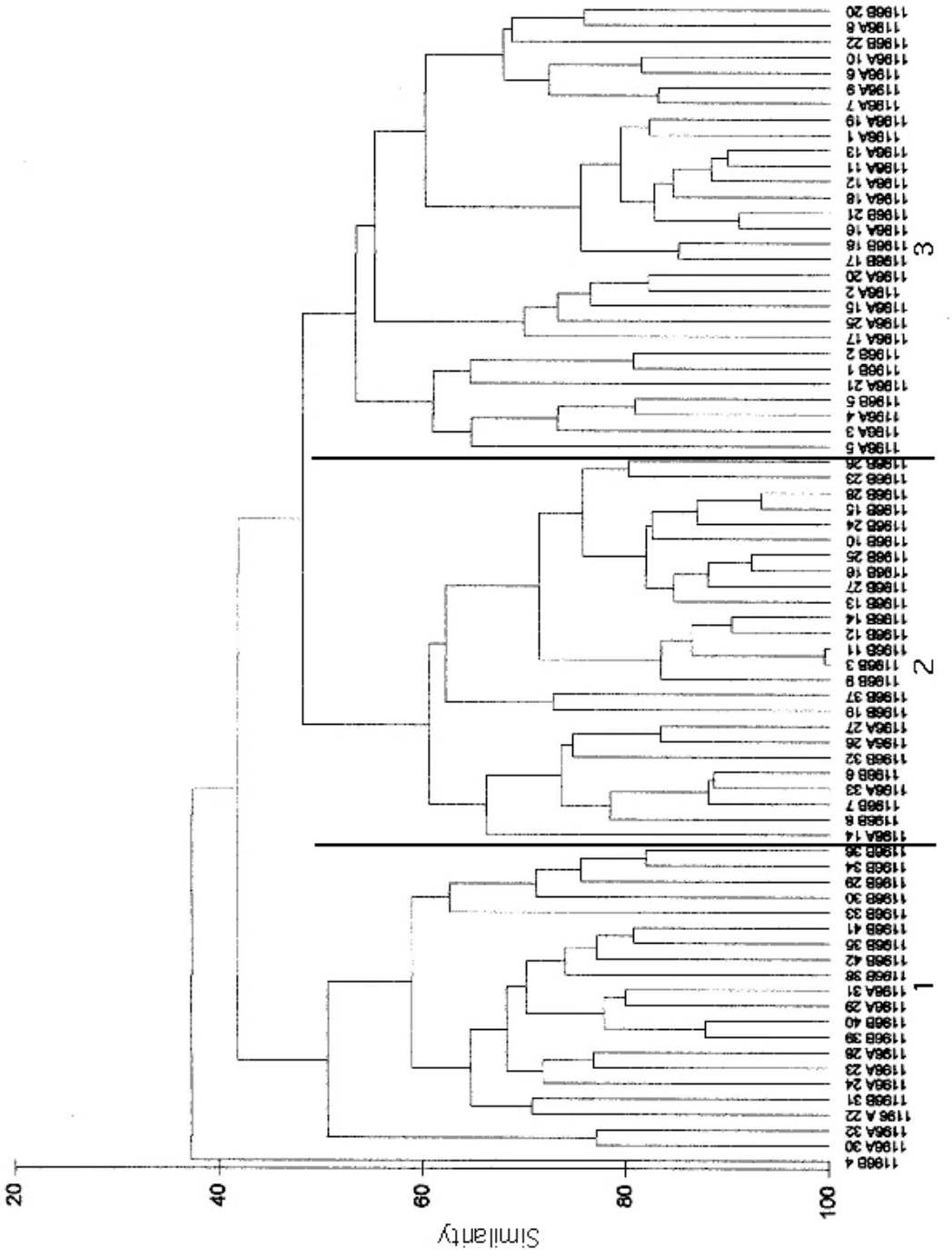


Figure 19 - Q-mode cluster analysis of southern platform (Site 1196) sediment data. Cluster numbers noted on figure are explained in the text.

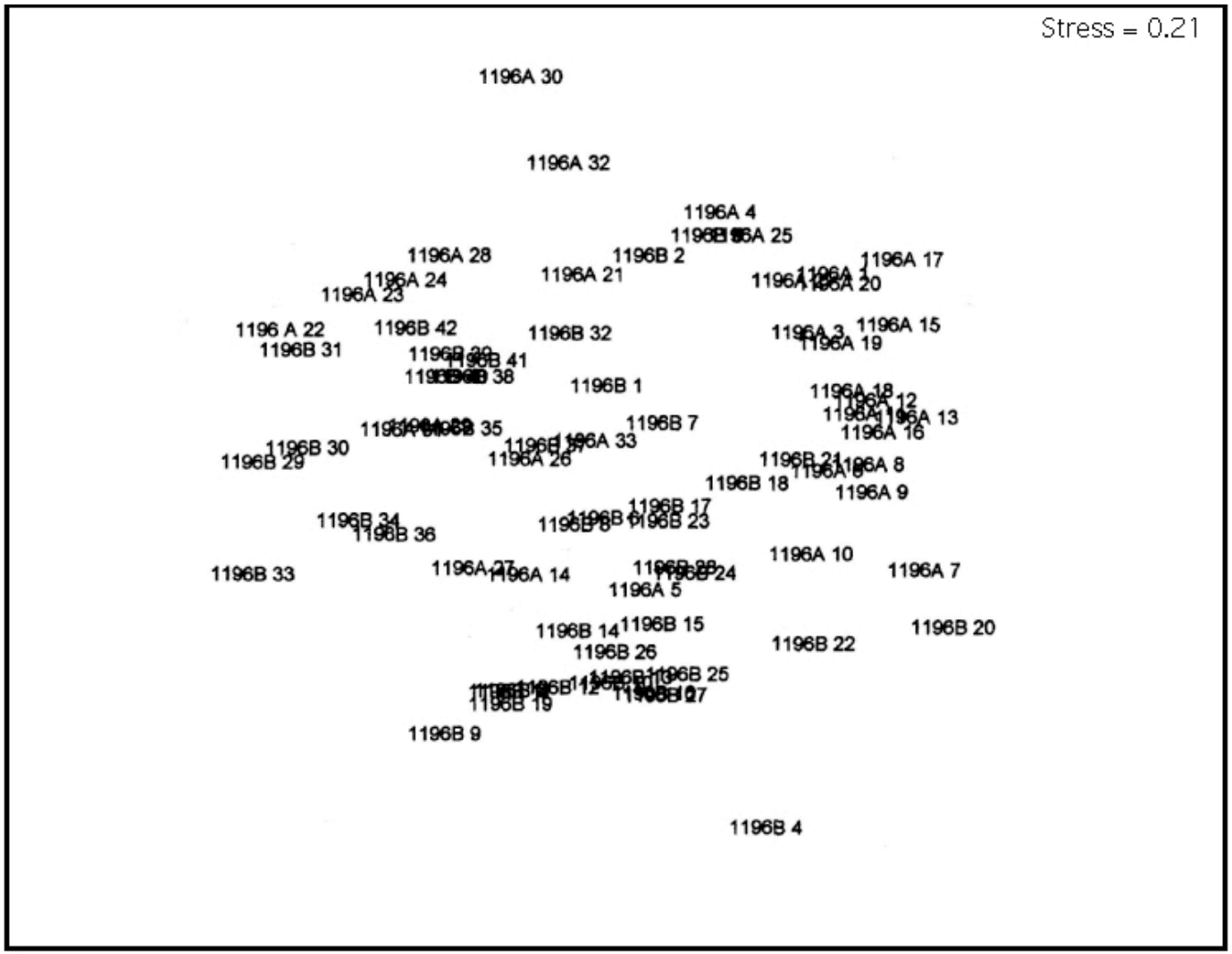


Figure 20 – Q-mode MDS plot of southern platform sediment data. Stress value of 0.21 indicates an unreliable representation of the data.

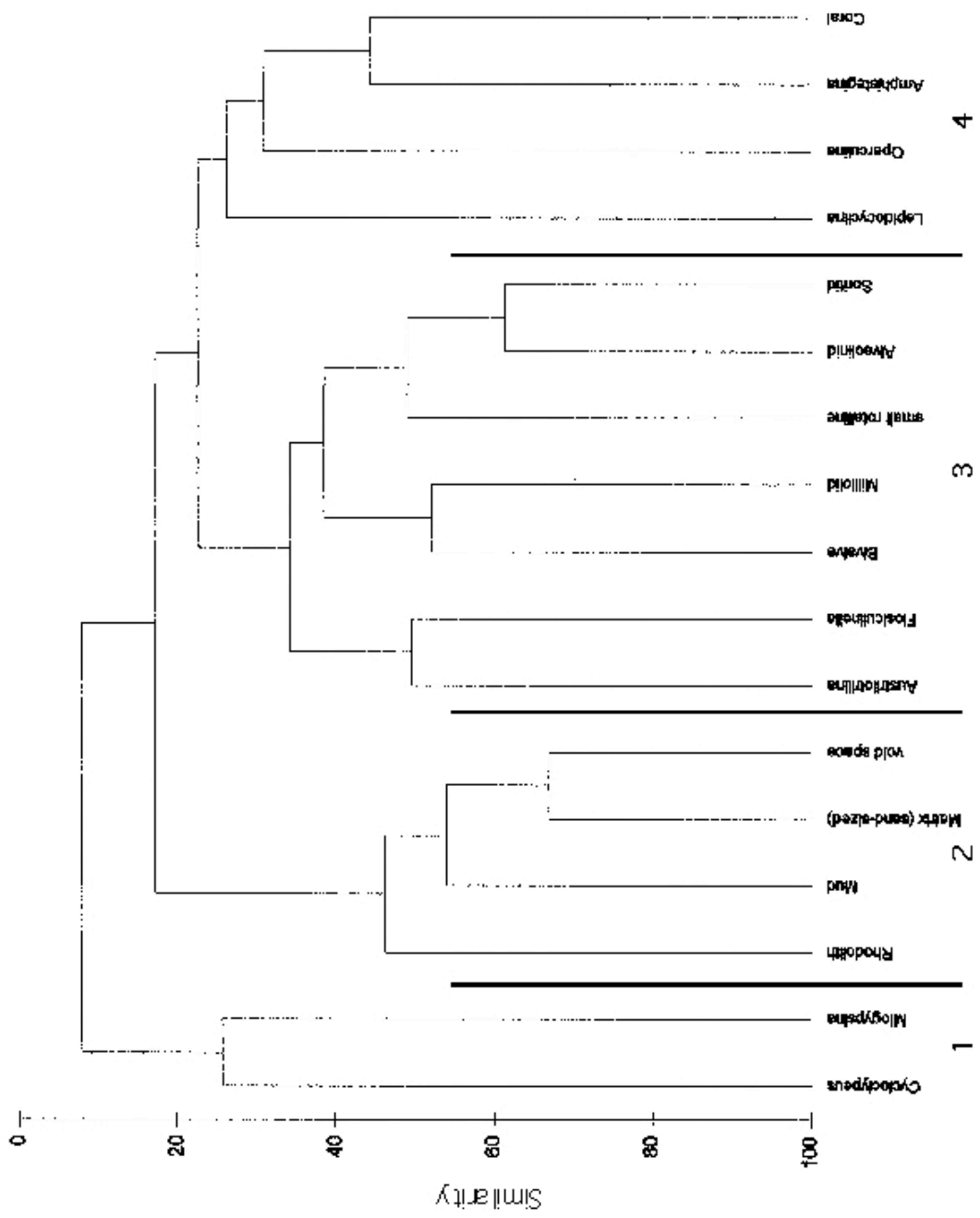


Figure 21 – R-mode cluster analysis of southern platform (Site 1196) sediment constituent data. Cluster numbers noted on figure are explained in the text.

constituents clustered together at ≥50% similarity, and were the most common sediment constituents found at Site 1196. The third cluster was composed of *Austrotrillina*, *Flosculinella*, bivalves, miliolids, small rotaliids, alveolinids and soritids; primarily the porcellaneous foraminifers found in Subunit IIA. These clustered together at ≥ 40% similarity, although taxa within the larger cluster grouped together more tightly. The fourth and final cluster was composed of *Lepidocyclina, Operculina, Amphistegina* and coral.

The results of MDS analysis (stress = 0.13) of the R-mode similarity differed slightly from the cluster analysis (Fig. 22). In the MDS analysis, *Amphistegina*, miliolids, bivalves and corals clustered together. Red algae, rhodoliths, void space and both mud- and sand-sized matrix clustered together. These two clusters represent similar constituents to those that might be found in a modern-day coral-algal reef environment; that is to say, fairly shallow, warm water with low nutrient levels and moderate hydrodynamic energy. As in the cluster analysis, the diverse group of porcellaneous foraminifers clustered tightly together. This cluster represents deposition in a restricted, very shallow-water environment, consistent with a sea-grass meadow. It is also likely that this assemblage, characteristic of the Subunit IIA interval, represents sedimentation during a time where the carbonate saturation state was higher. Coralline algae remained common in sediments from Subunit IIA, and several examples of a 'hooked' morphology of red algae were encountered (Fig. 18). The hooked algal morphology is considered diagnostic of a sea-grass environment (Bennington-Peavey *et al.*, 2004).

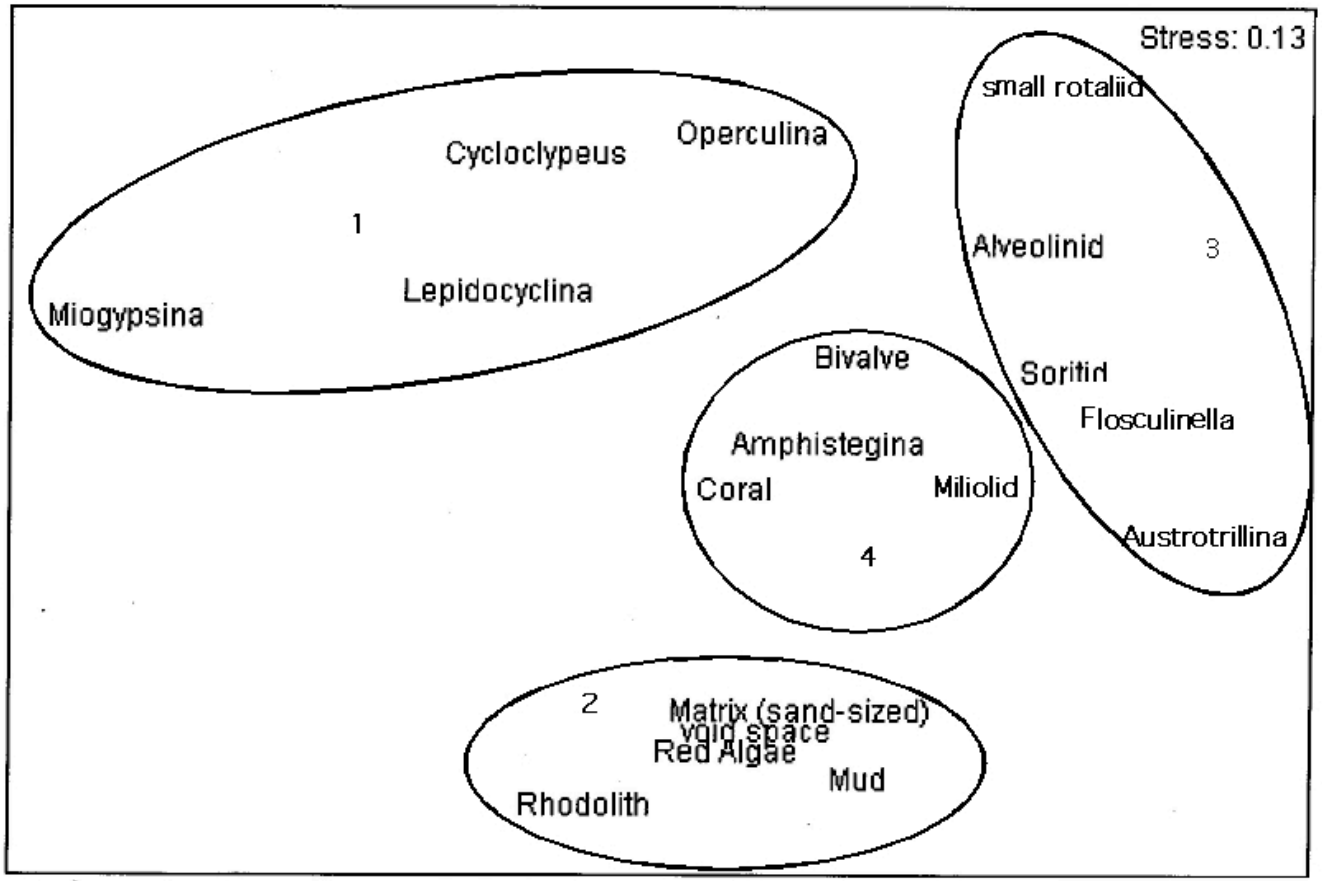


Figure 22 – R-mode MDS plot of southern platform (Site 1196) sediment constituent data. Stress value of 0.13 indicates reliable representation of the data. Interpretations made on figure are explained in the text.

The cluster analysis of R-mode similarity with foraminiferal taxa alone again loosely clustered *Cycloclypeus* and *Miogypsina* at ≥30% similarity (Fig. 23). This grouping is interpreted to represent deposition in a deep, oligophotic environment. The *Miogypsina* found at Site 1996, was more commonly the vermiform variety rather than the ovate form commonly found at Site 1193. The porcellaneous foraminifers common to Subunit IIA clustered together in this analysis at ≥40% similarity, with *Amphistegina* as a member of the cluster.

MDS representation of the R-mode similarity of foraminiferal taxa alone, confirmed the dendrogram produced by cluster analysis (Fig. 24; Stress = 0.08). In this case, the positions of foraminiferal taxa represented two trends: depth zonation and evolutionary status. Shallow-water, high-light taxa plotted towards the right of the figure, while oligophotic or oligophotic-tolerant taxa (*Miogypsina*, *Lepidocyclina* and *Cycloclypeus*) plotted to the left. Although *Operculina* tolerates oligophotic conditions, it is also found in low-light areas in shallow-water, for example, in the shady areas in and around coral reefs. This may be why *Operculina* plotted closer to the other reef-dwelling foraminifers. Extinct taxa (*Flosculinella*, *Austrotrillina*, *Lepidocyclina* and *Miogypsina*) plotted more distantly from extant taxa within groups.

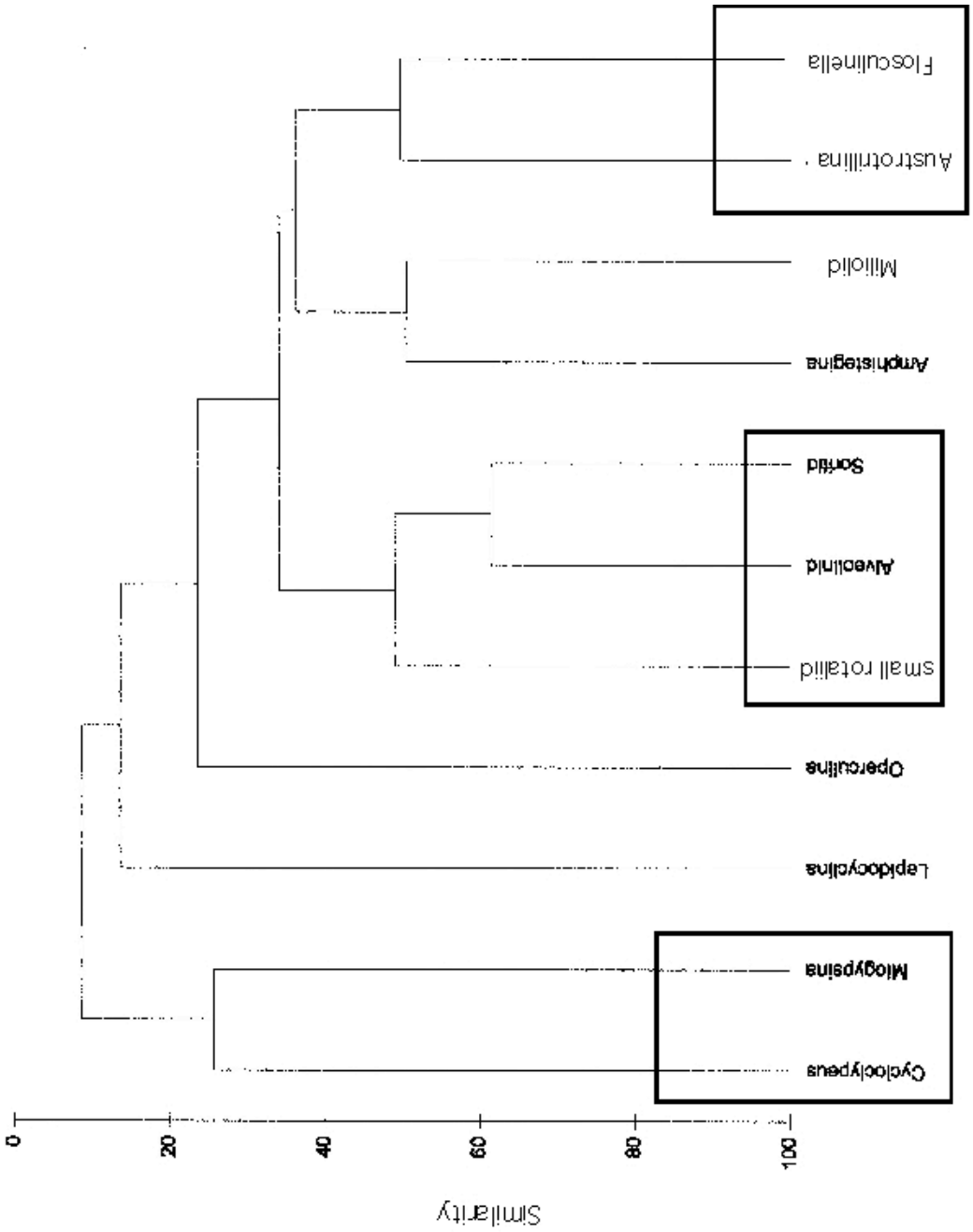


Figure 23 – R-mode cluster analysis of foraminiferal taxa from the southern platform (Site 1196).

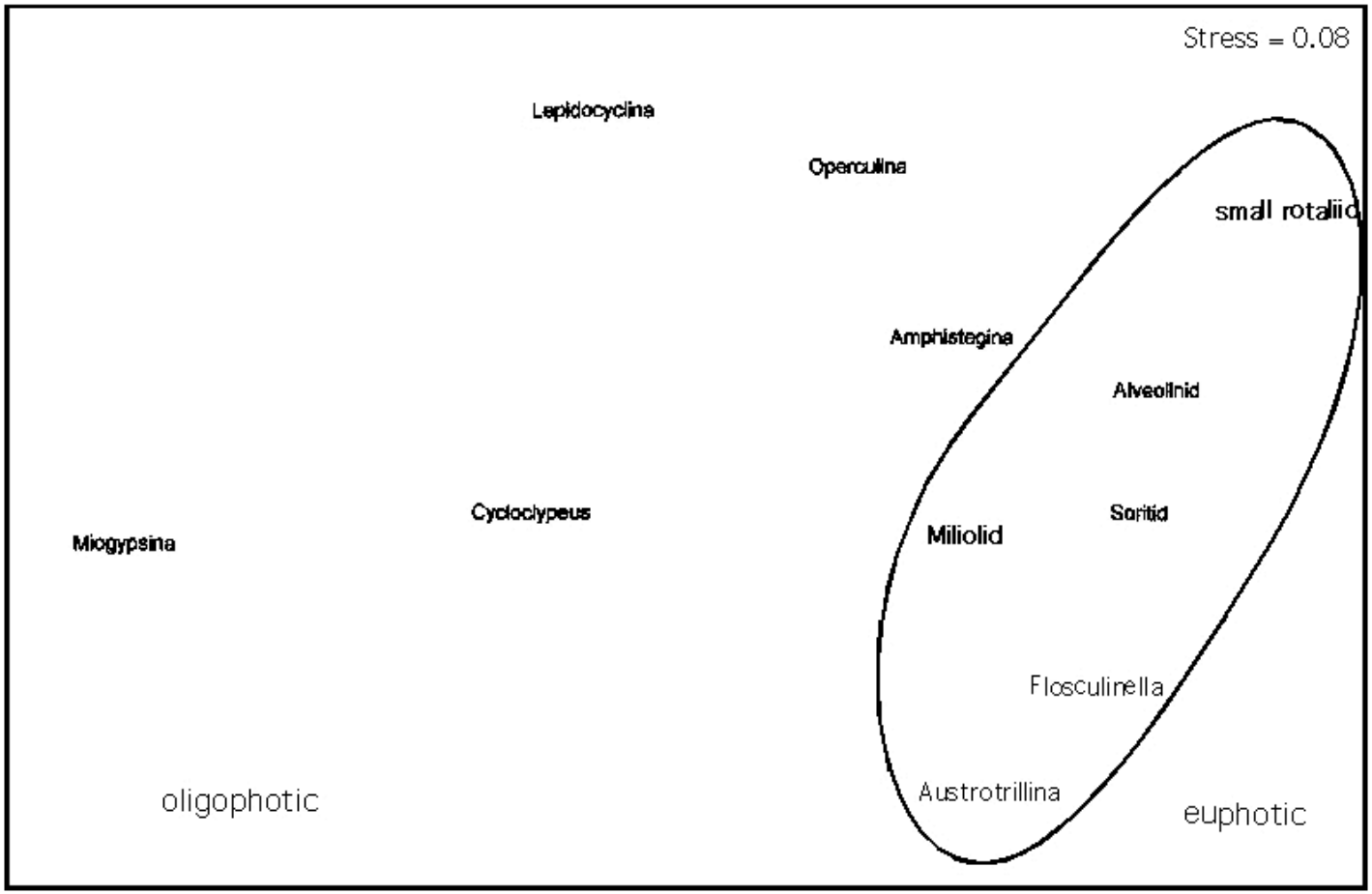


Figure 24 – R-mode MDS plot of foraminiferal taxa from the southern platform (Site 1196). Stress value of 0.08 indicates reliable representation of the data. Interpretations made on figure are explained in the text.

All Sites Combined

Principle Components Analysis clustered the majority of samples in a somewhat linear fashion (Fig. 25): the first two principle components explained 59.2% of the variation within the samples. End members of this trend represent bryozoan-rich samples and coralline red algae-rich samples. Samples from Site 1196 Subunit IIA plotted separately from this group. In this analysis, the two most important components to explain the variation among samples from Sites 1193, 1194 and 1196 are 1) the dominant sediment constituent (bryozoans or coralline red algae) and 2) the mineralogy and test ultrastructure of the foraminiferal assemblage (hyaline or porcellaneous tests).

Q-mode cluster analysis of samples from all sites created three major clusters of samples, each with several subordinate clusters (Fig. 26). The two major clusters separate samples from the northern platform sites from samples from the southern platform. There is more similarity among southern platform samples (approximately 60%) than among northern platform samples (approximately 55% similarity).

Within the major cluster of samples from site 1196, samples from subunit IIA clustered at a similarity of more than 70% (noted as cluster 1 in Fig. 26). These are the samples dominated by *Flosculinella* and *Austrotrillina*, as well as alveolinids, soritids and small miliolids. As noted previously, these samples are interpreted to have been deposited in a shallow, high-light, high-energy, restricted environment, consistent with a sea-grass meadow.

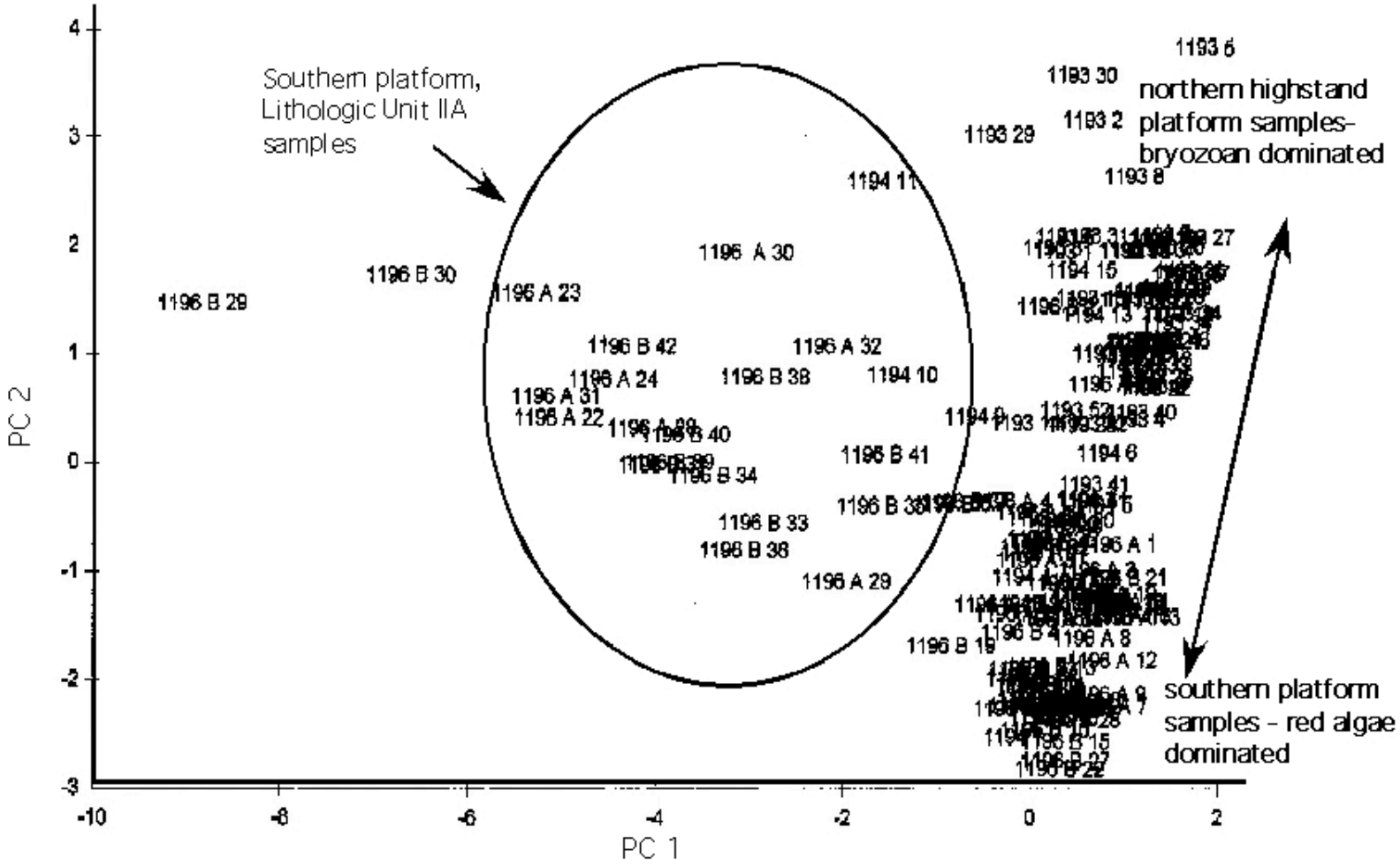


Figure 25 - Principle Components Analysis of samples from the northern highstand platform (Site 1193), northern lowstand platform (Site 1194) and the southern platform (Site 1196). The first two principle components explain 59.2% of the variation between samples. Interpretations noted on the figure are explained in the text.

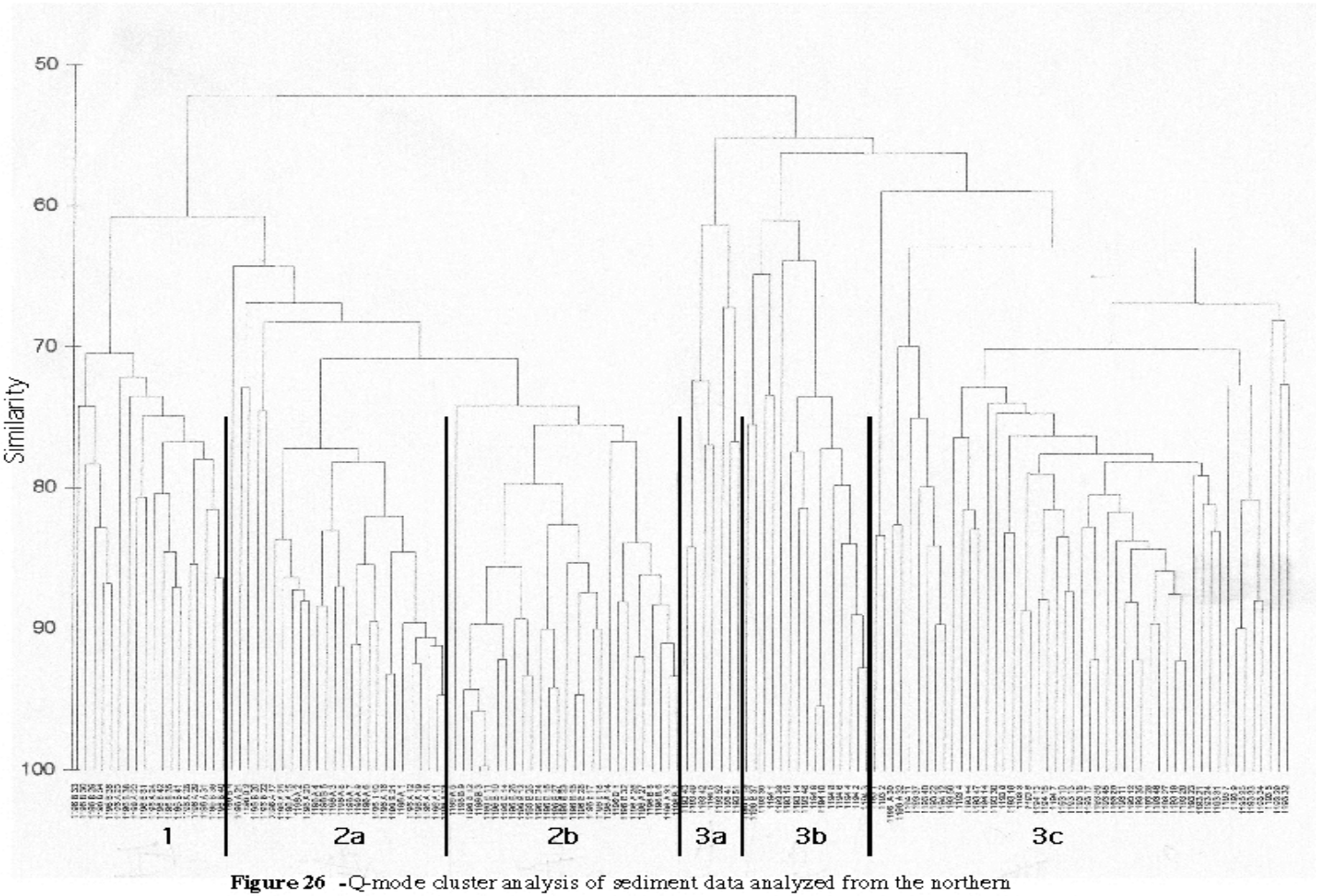


Figure 26 -Q-mode cluster analysis of sediment data analyzed from the northern highstand platform (Site 1193), northern lowstand platform (Site 1194) and the southern platform (Site 1196). Numbered groupings are explained in the text.

The second cluster composed of samples from Site 1196 is clustered at approximately 60% similarity. This cluster is comprised of the majority of samples from Site 1196, that is to say, from all lithologic units examined from Site 1196 except Subunit IIA. These samples are further subdivided on the basis of mud or sand-sized matrix content and degree of recrystallization. The cluster 2a is composed of samples with both mud and sand-sized matrix and clustered at approximately 65% similarity. *Lepidocyclina* and *Amphistegina* are fairly common in these samples, which are dominated by the presence of coralline red algae. Cluster 2b, on the other hand, is composed of moderately recrystallized samples, in which LBF taxa mostly occur as molds and were, therefore, not always identifiable. *Amphistegina* was the most commonly identifiable LBF taxon in these samples. Cluster 2b was grouped together at approximately 75% similarity. Samples in cluster 2b contain more rhodoliths than those grouped into cluster 2a. This is interpreted to indicate an increase of hydrographic energy at the times in which samples grouped into cluster 2b were deposited.

The third cluster was much less well-defined than the cluster containing samples from Site 1196 and consists of several sub-clusters. This cluster was composed of samples from both Sites 1193 and 1194, and occasional samples with low coralline algae content from Site 1196. The first sub-grouping in the second cluster, noted as 3a, grouped together at ≥55% similarity. This group is composed of samples in which *Operculina* was the dominant LBF taxa. *Cycloclypeus* also occurred in this grouping occasionally. This group is interpreted to indicate periods of oligophotic deposition.

Cluster 3b is also interpreted to indicate periods of oligophotic deposition. This cluster also grouped together at a similarity of ~57%. The major difference between the first group and this second one is that *Cycloclypeus* and *Lepidocyclina* were much more common in this grouping. Also, this cluster included two samples from site 1196 that are particularly low in red algae. Most of the samples in this cluster were highly recrystallized.

The final sub-cluster, 3c, clustered at a similarity of ≥60%. This final grouping is the most diverse of the clusters in this dendrogram and includes the majority of samples from Site 1193 as well as the samples from Site 1194 that were influenced by shallow-water deposition. *Amphistegina*, *Lepidocyclina*, and ovate *Miogypsina* were the dominant LBF taxa. These samples are dominated by bryozoans, with occasional coral fragments and are interpreted to have been deposited in open-shelf euphotic conditions, possibly between 20 and 50 meters depth (Hallock *et al.,* submitted). LBF morphologies in these samples are more robust than those in the first two sub-clusters.

MDS representation of the Q-mode similarity data (Fig 27; stress = 0.21) confirms only the two major clusters from the dendrogram. Samples from the southern platform are grouped at a slight distance from samples from both northern platforms sites, with some overlap in the two groups. The stress-level for this MDS analysis is too high, however, to make reliable interpretations of the multi-dimensional data.

R-mode cluster analysis of samples from all sites broke sediment constituents into four main clusters, with a number of outliers (Fig. 28). The outliers included globorotalid foraminifers, gastropods and cements. The first cluster is composed of the distinct group

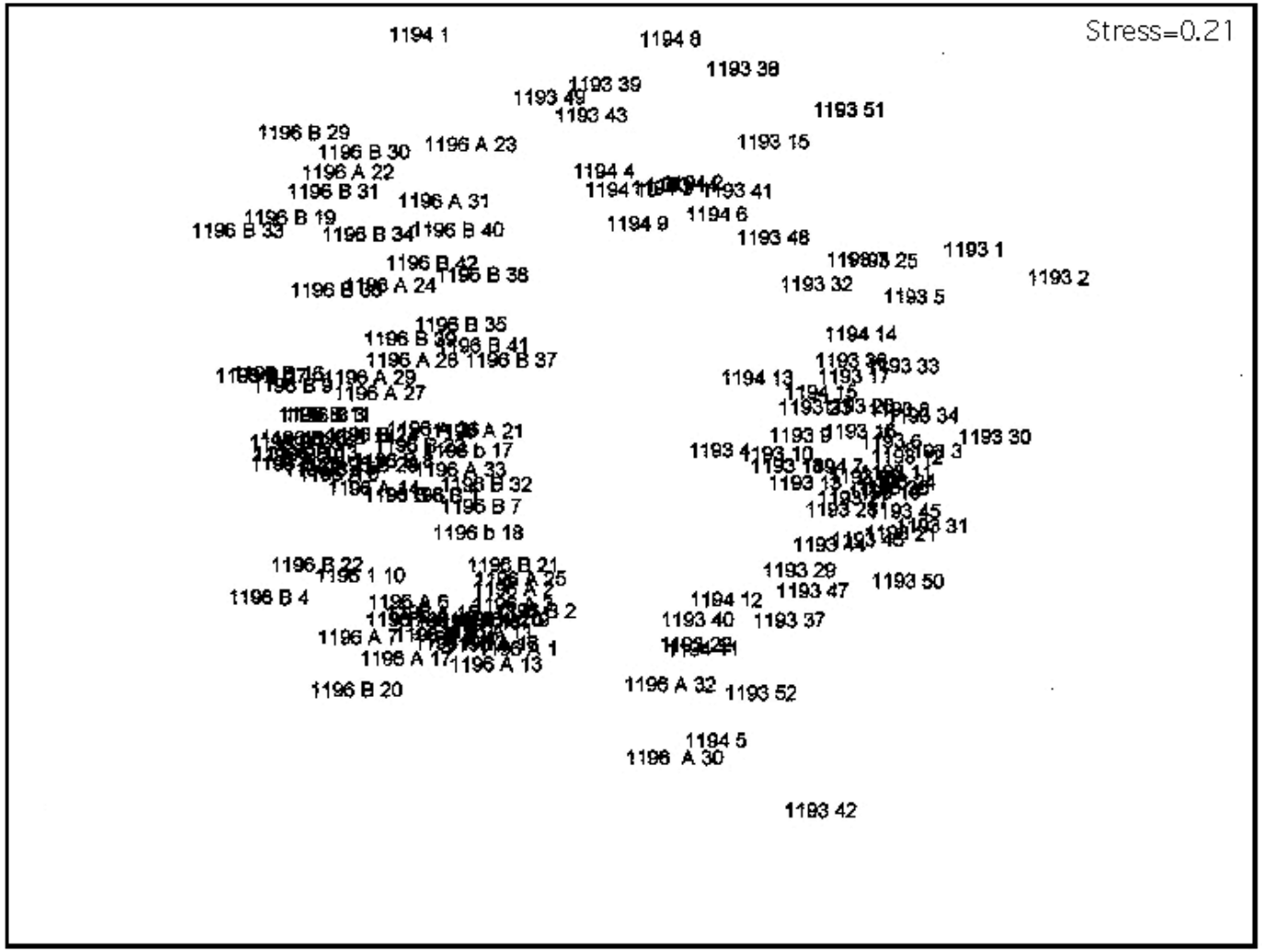


Figure 27 – Q-mode MDS plot of all samples analyzed from northern highstand platform site 1193, northern lowstand platform site 1194 and southern platform site 1196. Stress value of 0.2. indicates unreliable representation of the data.

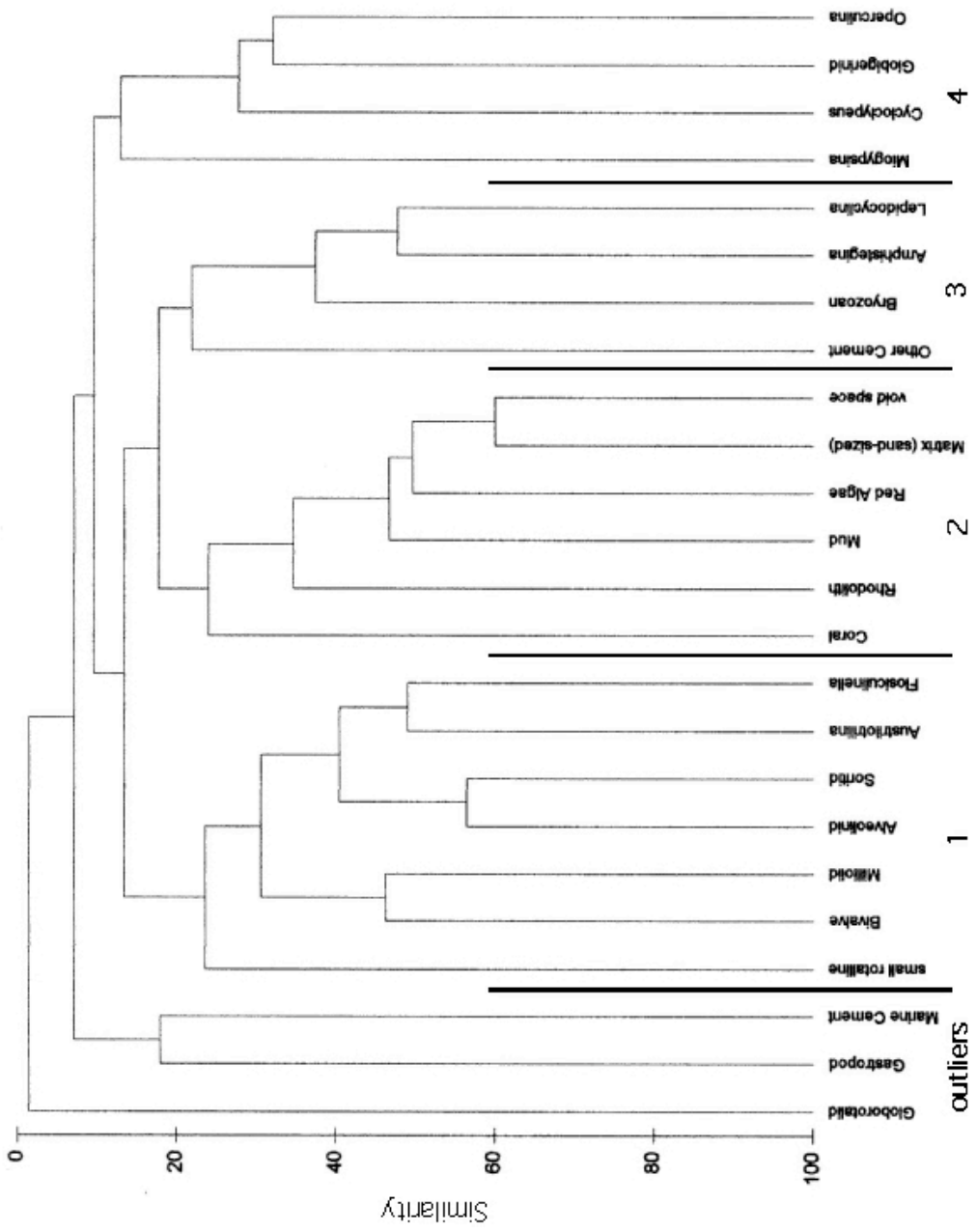


Figure 28 – R-mode cluster analysis of sediment constituents analyzed from the Northern Highstand Platform (Site 1193), the Northern Lowstand Ramp (Site 1194) and the Southern Platform (Site 1196).

of foraminifers found at Site 1196, lithologic subunit IIA: *Austrotrillina*, *Flosculinella*, soritids, alveolinids, small rotaliids and miliolids. Cluster 1 grouped at a similarity of ≥25%. Within the major cluster, however, *Austrotrillina* and *Flosculinella* clustered at a similarity of ≥50%, as did soritids and alveolinids. Cluster 2 is composed of corals, rhodoliths, mud, red algae, sand-sized matrix and void space (primary and secondary porosity), and also clustered at a similarity of approximately 25%. The third cluster was composed of bryozoans, *Amphistegina* and *Lepidocyclina* and clustered at ~25% similarity. Within the third cluster, *Amphistegina* and *Lepidocylina* clustered at a similarity of ≥50%. The final cluster, cluster 4, is composed of *Cycloclypeus*, *Operculina* and globigerinid foraminifers and clustered at ≥25 % similarity, with *Miogypsina* as an associated outlier.

MDS representation of R-mode similarity data confirmed these groupings (Fig. 29; Stress =0.18). Taxa tolerant of oligophotic, deeper-water conditions plotted towards the left of the figure, while euphotic, shallower-water taxa plotted towards the right of the figure.

R-mode cluster analysis with foraminiferal taxa alone broke foraminiferal taxa into two groups (Fig. 30). Globorotalid foraminifers were classed as an outlier to these clusters. The first cluster is composed of the diverse taxa found in Site 1196 subunit IIA: miliolids, alveolinids, soritids, small rotalliids, *Austrotrillina* and *Flosculinella*. The second cluster is composed of the hyaline foraminiferal taxa found in the majority of Marion Plateau platform sediments: *Amphistegina, Lepidocyclina, Cycloclypeus, and Operculina,* as well as globigerinid foraminifers, with *Miogypsina* loosely associated.

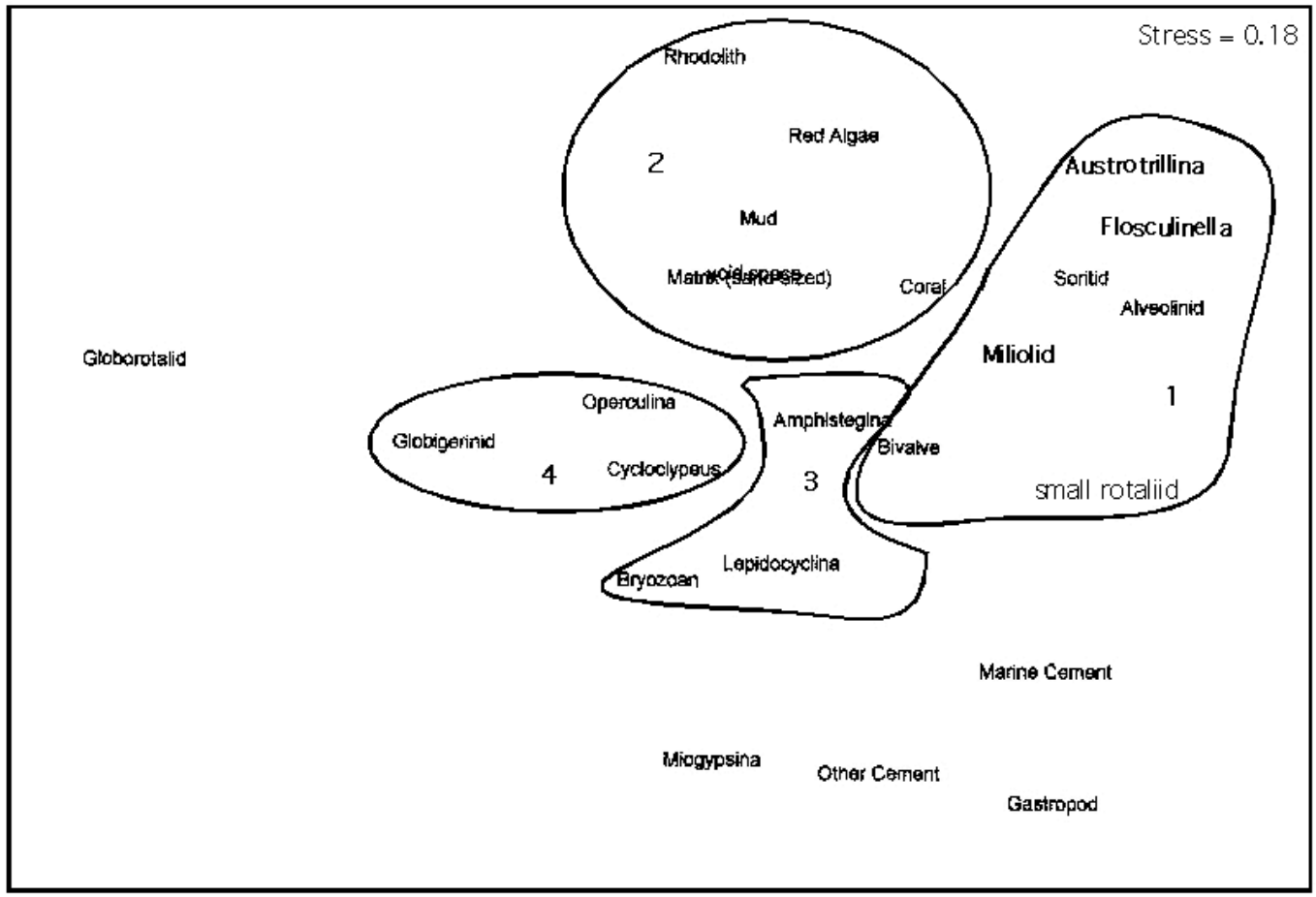


Figure 29 – R-mode MDS plot of sediment constituents from the northern highstand platform (Site 1193), northern lowstand platform (site 1194) and the southern platform (Site 1196). Stress value of 0.18 indicates a somewhat reliable representation of the data. Interpretations noted on figure are explained in the text.

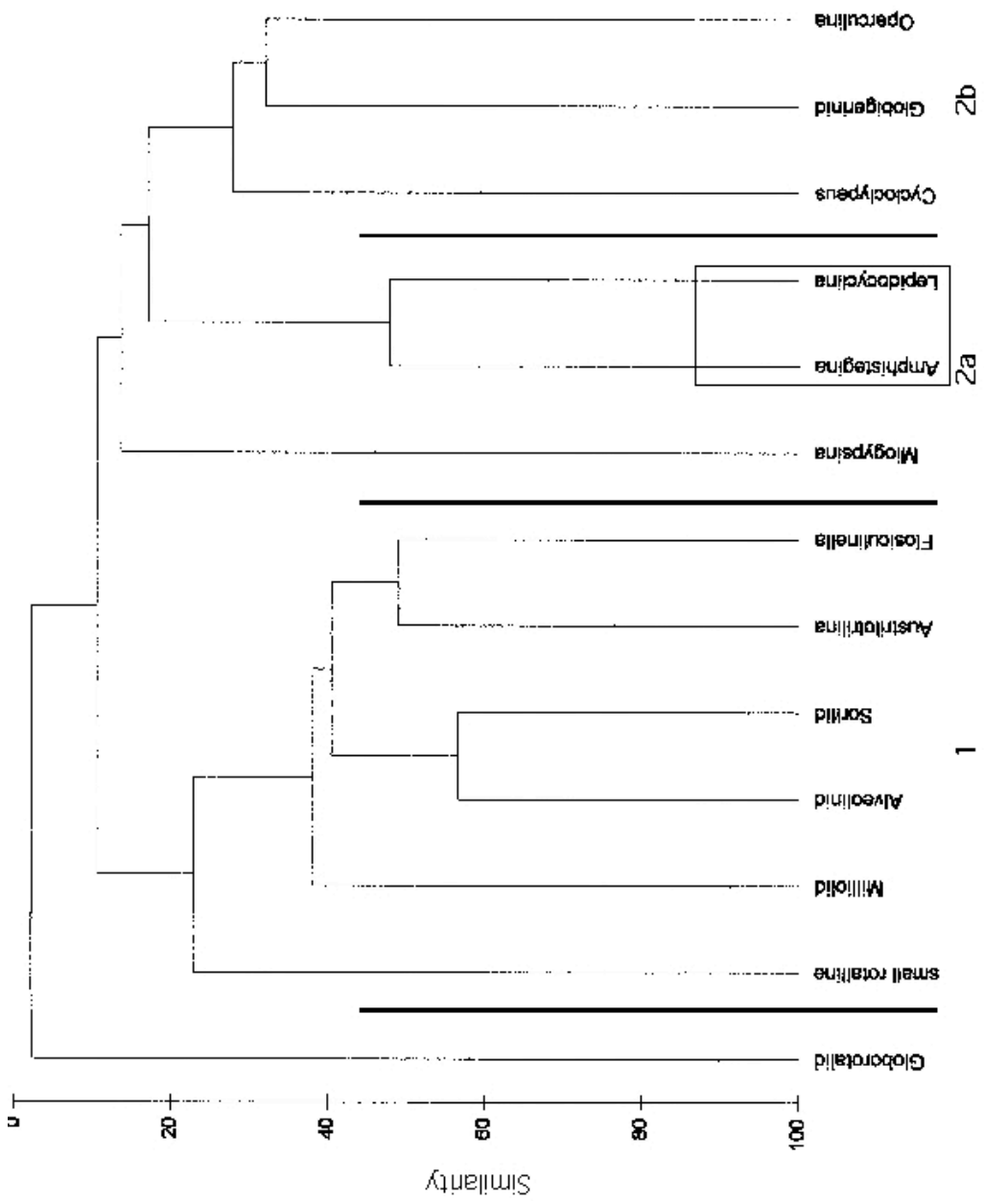


Figure 30 – R-mode cluster analysis of foraminiferal taxa for data from the northern highstand platform (Site 1193), northern lowstand platform (Site 1194) and the southern platform (Site 1196). Numbered groupings are explained in the text.

The relatively loose association of *Miogypsina* with other foraminifers is likely due to the fact that two distinct morphologies are considered here, the vermiform, and the ovate varieties. Had these morphologies been distinguished, *Miogypsina* morphotypes might have grouped more closely with other foraminiferal genera.

MDS representation of the similarity data (stress = 0.09) plotted these foraminifers in a similar manner (Fig. 31). Taxa were distributed in three directions with *Amphistegina* at the center. Taxa with extant representatives (soritids, alveolinids, and other miliolids) plotted closer to *Amphistegina* than extinct taxa. The rotaliid LBF taxa with extant representatives (*Cycloclypeus* and *Operculina*) plotted between *Amphistegina* and the globigerinids. The extinct rotaliid taxa, plotted as a third axis, with *Lepidocyclina* closer to *Amphistegina* than *Miogypsina*. The assemblage from site 1196 subunit IIA plotted towards one side of the figure, the other LBF taxa were spread out with *Amphistegina* closer to the porcellaneous foraminifers. As in the dendrogram, globorotalids plotted at a distance from the other groups, beyond the globigerinids.

The plotting of foraminiferal taxa in multi-dimensional space along evolutionary lines (taxa with extant representatives grouping together and extinct taxa grouping at a distance) is fascinating, and an unexpected result of this project. That extinct taxa plotted separately from taxa that are still alive today suggests the presence of ecological or oceanographic niches that are either no longer available to these foraminifers (leading to their extinction) or for which these taxa have been outcompeted by other foraminiferal groups, as in an environmental bottleneck.

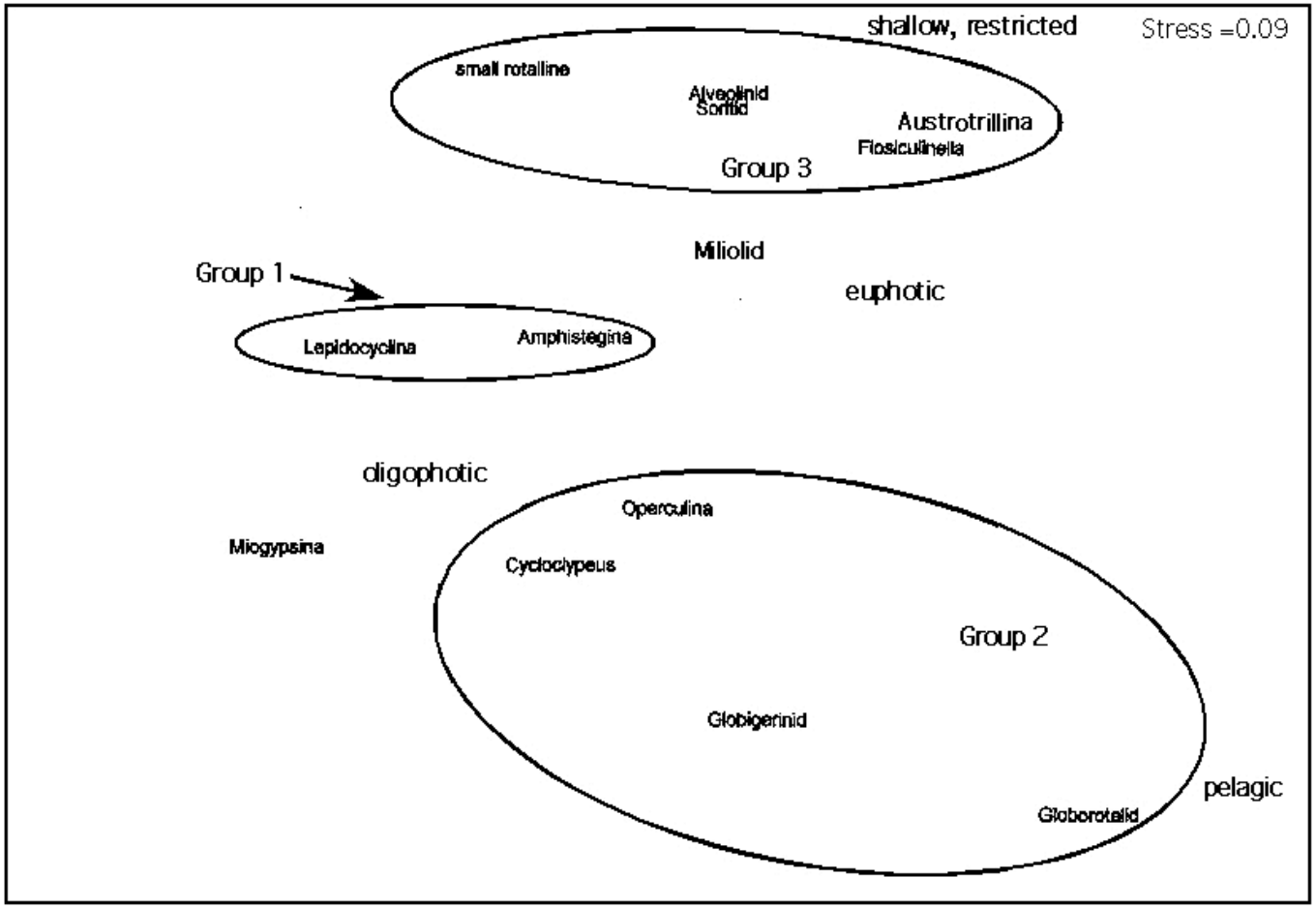


Figure 31 – R-mode MDS plot of foraminiferal taxa for data from the northern highstand platform (Site 1193), northern lowstand platform (Site 1194) and the southern platform (Site 1196). Interpretations on figure are explained in the text. Stress value of 0.09 indicates reliable representation of the data.

Discussion

Comparing the summary figures from each of the three sites (Figs. 32, 33, 34) highlights the fundamental paleoenvironmental and paleowater-depth differences between the three sites. For the purposes of this analysis, the three groups of paleoenvironmentally relevant foraminiferal taxa are deemed representative of three distinct environmental end-members. Group 1 consists of *Amphistegina* and *Lepidocyclina*. Domination of the total assemblage by members of this group is interpreted to represent sedimentation in unrestricted, open-shelf, euphotic environments, possibly up to 50 m water depth. Group 2 includes *Cycloclypeus*, *Operculina* and planktonic foraminifers and domination by this group is interpreted to represent either sedimentation at oligophotic water depths, generally from 50m to 100m water depth, or transport of benthic components from such an environment. Group 3 is a group of foraminifers primarily found at Site 1196, lithologic subunit IIA and includes *Austrotrillina*, *Flosculinella*, alveolinids, and soritids. Domination by this group is interpreted to represent deposition in a very shallow, restricted marine setting, in less than 20 m water depth. In cluster analyses, miliolids and small rotaliids often clustered with Group 3 taxa, but are not reliable indicators of paleoenvironment on their own.

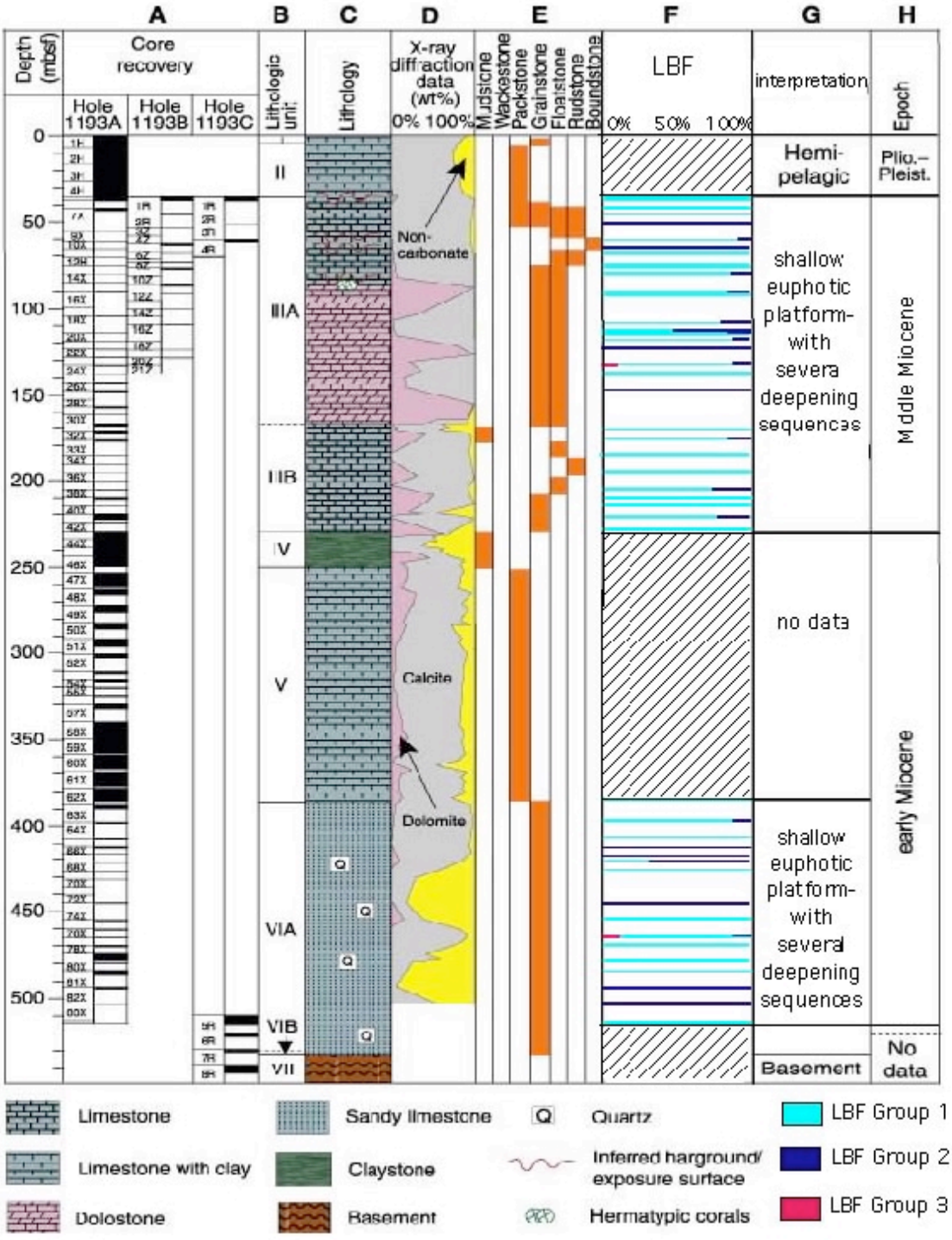


Figure 32 – Percent occurrence of paleoenvironmentally relevant taxa from the northern high stand platform drilled at Site 1193. Modified from Shipboard Scientific Party, 2002.

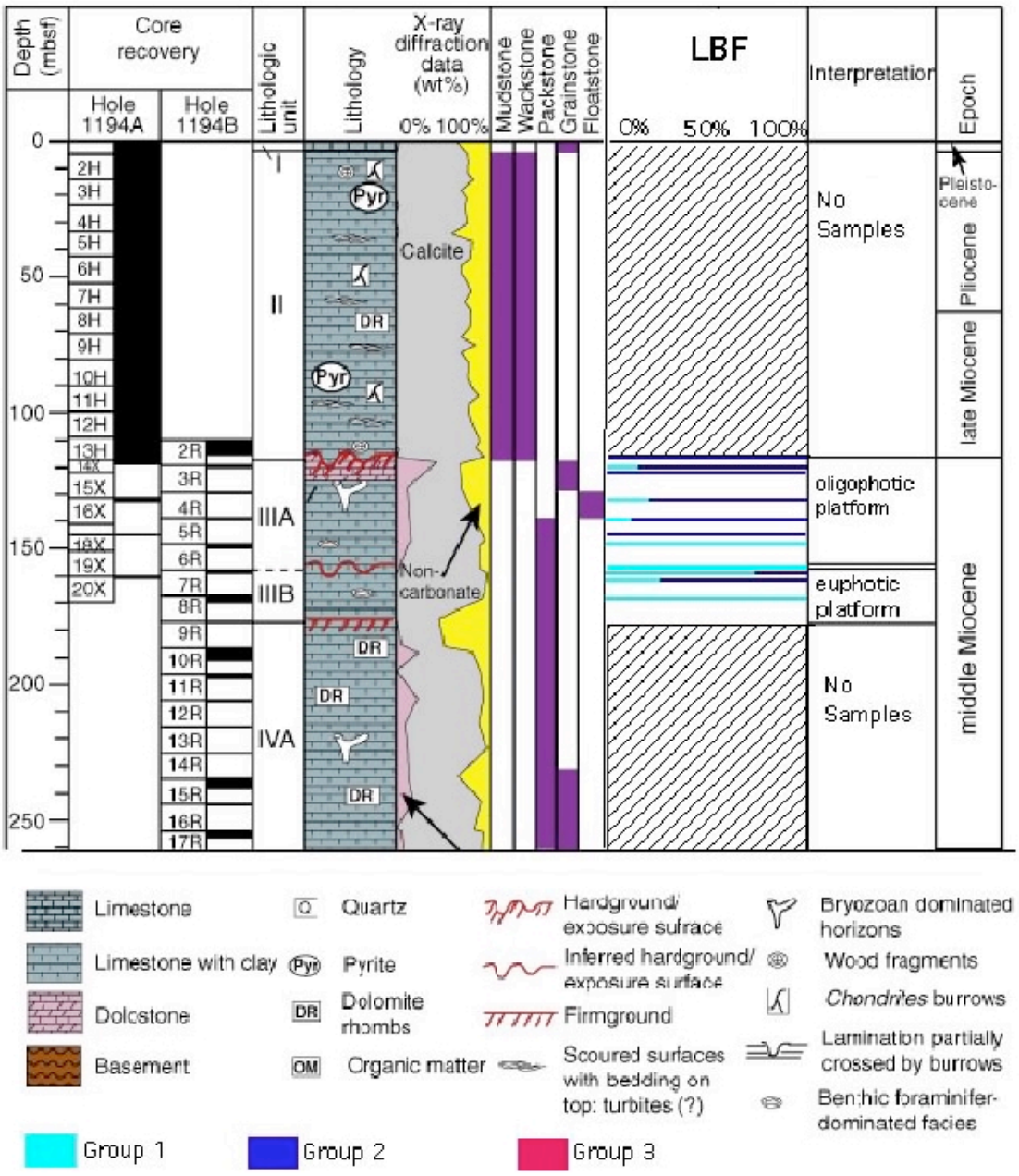


Figure 33 - Percent occurrence of paleoenvironmentally relevant taxa from the northern lowstand platform drilled at Site 1194. Modified from Shipboard Scientific Party, 2002.

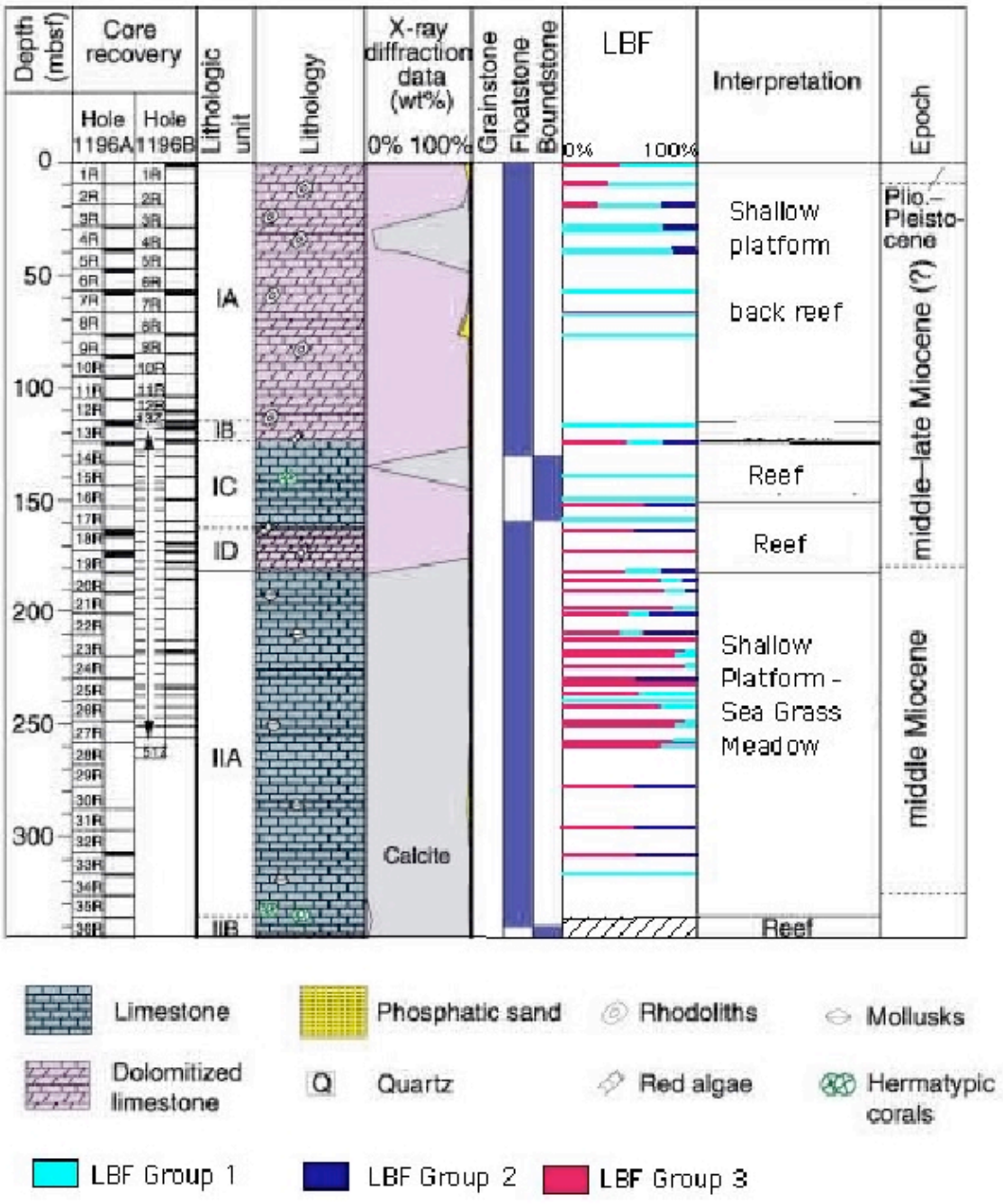


Figure 34 - Percent occurrence of paleoenvironmentally relevant taxa from the southern platform drilled at Site 1196. Modified from Shipboard Scientific Party, 2002.

Paleowater depth can be a difficult parameter to unravel, as it is a fundamentally composite environmental factor, intimately tied to temperature, water transparency and hydrographic energy (Hohenegger, 2000, 2004). This means that, although it is possible to estimate paleowater-depth ranges, it is extremely difficult to pinpoint exact depths at which deposition occurred. Changes in any one of the parameters that relate to how we conceive of water depth can significantly alter the way organisms respond to the other parameters.

Northern Highstand Platform

The neritic sediments found on the northern highstand platform represent sedimentation by a diverse bryozoan community in which larger benthic foraminifers were an important component. The foraminiferal assemblages found in all of the units studied from Site 1193 are characteristic of Early to Middle Miocene associations (Chaproniere, 1983; Hallock *et al.,* submitted). The metazoan assemblage bears the hallmark of the heterozoan assemblage discussed by James (1997), which is commonly associated with cool-water carbonates or carbonates from subeuphotic depths. The concordance of larger benthic foraminifers indicates euphotic (0-50m water depth) to oligophotic (50-100m water depth) depths, and likely cool subtropical temperatures.

Overall, the dominance of LBF assemblages by Group 1 (*Amphistegina* and *Lepidocyclina*) indicates platform deposition at less than 50m water depth (Fig. 32). Several deepening sequences are indicated by the dominance of Group 2 taxa (*Cycloclypeus* and *Operculina* primarily), in some intervals. These deepening sequences may indicate that higher-order sea-level changes are recorded in northern platform sediments.

The abundance of LBF *in situ* in sediments recovered from the northern highstand platform rules out the possibility of an aphotic carbonate factory operating at this site during platform deposition. The bryozoan-dominated assemblage, indicates, however, that oceanographic conditions were not suitable for coral-reef development. Porcellaneous LBF such as *Flosculinella* and *Austrotrillina* are exceedingly rare in sediments recovered from Site 1193. Indeed, the only members of Group 3 taxa present in these samples are small rotaliids and miliolids, neither of which are particularly useful indicators of paleowater depth. The scarcity of porcellaneous larger foraminifers, as well as zooxanthellate corals and *Halimeda*, may be an indication of carbonate saturation state below the threshold for coral-reef development (Kleypas *et al.,* 1999).

Kumar and Saraswati (1997) proposed that LBF taxa respond differently to environmental parameters in mixed carbonate-siliciclastic environments than in "purely" carbonate environments. Fluvial input affecting sedimentation on the northern Marion Plateau might have reduced water transparency at Site 1193, while current regimes producing hydrographic energy at that site remained more similar to much shallower water environments. The foraminiferal assemblages at Site 1193 are consistent with this

hypothesis, as the assemblages are a mix of taxa that one might expect from both higher-energy and lower-light conditions. The terriginous input, evidence for which is found in the abundance of siliciclastic grains in Site 1193 sediments on the northern platform, might also serve to explain why few corals were present on the northern highstand platform (Shipboard Scientific Party, 2002).

Northern Lowstand Ramp

Paleoenvironments at Site 1194 were bimodally distributed (Fig. 33). The upper part of the sequence sampled is fine grained and the LBF assemblage is dominated by Group 2 taxa: *Cycloclypeus*, *Operculina* and planktonic foraminifers. Chaproniere (1975) identified the grouping of these taxa as indicative of low-energy oligophotic environments, below storm-wave base. The lower part of the sequence, however, is much sandier and the dominant LBF in this section are Group 1 taxa: *Amphistegina* and *Lepidocyclina*. As at Site 1193, the Group 3 taxa present in sediments from Site 1194 are small rotaliids and miliolids, which are not reliable indicators of paleowater depth. However, LBF are relatively sparse within this lower interval. As a consequence, neither assemblage definitively indicates *in situ* deposition.

Southern Platform

Deposition at Site 1196 took place in moderate to shallow water depths. LBF taxa are overwhelmingly from Group 1 and 3 taxa (Fig. 34). Group 2 taxa dominated in very few intervals. Sedimentation at Site 1196 is almost entirely euphotic, as opposed to the oligophotic assemblages seen in many intervals from the northern highstand platform drilled at Site 1193. Porcellaneous foraminifers such as *Austrotrillina* and *Flosculinella* are abundant in samples from lithologic subunit IIA. Large segments of the sediment cores recovered from southern platform do not contain any identifiable LBF, due to recrystallization and dolomitization of platform sediments. In these heavily recrystallized intervals, LBF occur primarily as molds that can only occasionally be identified to the genus level. These recrystallized units are represented as blank areas in the Site 1196 summary figure (Fig. 34)

Quantitative analysis of foraminifers from subunit IIA indicates deposition in a shallow-water, high-energy environment, consistent with a sea-grass meadow. Other sedimentological constituents support this hypothesis, including the abundance of gastropods and the presence of a hooked morphology of red algae in subunit IIA samples (Fig. 18). Bennington-Penney *et al*. (2004) postulate that this morphology of coralline red

algae can be used to diagnose macrophyte-vegetated environments, such as sea-grasses, in the sedimentary record.

As discussed in the Leg 194 Initial Report (Shipboard Scientific Party, 2002), interpreting paleoenvironment and paleowater depth can be problematic for Site 1196 due to extremely low recovery. Coralline red algae and rhodoliths are found in all parts of the photic zone, from euphotic to oligophotic environments. LBF adaptations to oligophotic conditions (thin, flat tests) were only very rarely seen, however. The majority of LBF morphologies in sediments recovered from Site 1196 were robust, indicating a shallow marine environment with some degree of hydrodynamic energy.

Comparing Qualitative and Quantitative Analyses of Foraminiferal Assemblages

The major objective of this project was to refine qualitative paleoenvironmental interpretations made shipboard during Leg 194 using quantitative methodologies. Quantitative and qualitative analyses yielded generally consistent results. Comparing the results of this project to previous qualitative assessments of paleoenvironment and paleowater depth (Shipboard Scientific Party, 2002; Hallock *et al.,* submitted) quantitative analyses do offer some refinements to the results of qualitative analyses.

At the northern highstand platform site, the results of qualitative analysis of benthic foraminiferal assemblages (Shipboard Scientific Party, 2002) were similar to the results of the quantitative analyses in this project. Both analyses found evidence for at

least some oligophotic sedimentation at Site 1193. Qualitative analysis interpreted paleowater depths to be mostly between 60m and 100m (Shipboard Scientific Party, 2002), while my quantitative analysis interpreted the vast majority of samples as having been deposited in ~20- 50 m water depth. Only a few samples were interpreted as having been deposited in more than 50m water depth (Fig. 32). The few Group 3 taxa present in sediments from the northern highstand platform, primarily smaller miliolids and rotaliids, were not particularly paleoenvironmentally definitive.

The lowstand ramp inferred at the northern lowstand site, 1194, was largely uninterpreted with respect to paleoenvironment by Shipboard Scientific Party (2002). Quantitative assessments (Fig. 33) have demonstrated that the photic-zone sediments found at Site 1194 were not necessarily deposited in the same water depths. Rather, there are two distinct phases of photic-zone sediments: euphotic sedimentation, or transport from the euphotic zone, from approximately 150 to 170 mbsf, and oligophotic sedimentation from approximately 117 to 150 mbsf. This implies that, assuming photic taxa were deposited *in situ*, the record of the lowest sea-level lowstand at Site 1194 lies somewhere between 150 and 170 mbsf. This is a vast improvement over the qualitative analyses conducted shipboard, which posited a paleowater depth of less than 60m for the entire interval from 119 mbsf to 158 mbsf, and did not resolve a paleowater depth for the other samples in the lithologic unit.

Qualitative (Shipboard Scientific Party, 2002) and quantitative (Fig. 34) analyses of benthic foraminiferal assemblages recovered from the southern platform were also very similar. Qualitative analyses led to an interpretation of very shallow-water

deposition on the southern platform (Shipboard Scientific Party, 2002), as did my quantitative analyses. Qualitative analyses were used to interpret paleowater depths in recrystallized facies, while the quantitative methods used in this project were unable to utilize morphological descriptors of LBF molds found in these facies.

The similarity between the qualitative and quantitative results, despite the different techniques utilized, may be because the qualitative analyses discriminated between different morphotypes and species of LBF, whereas the quantitative analyses identified LBF taxa to the genus level only. The identification of LBF taxa to morphotype added specificity to the qualitative analysis that was absent from the quantitative analysis, despite the increased rigor of quantitative analyses.

The Southern and Northern Platforms: Why Are They So Different?

The depositional histories of the northern and southern platforms are significantly different. Interpretations of quantitative sedimentological data elucidate the environmental differences between the two locations. Biotically, the two platforms are similar in one aspect only: the preserved LBF assemblages. The LBF on both the northern and southern platforms are dominated by *Amphistegina* and *Lepidocyclina*.

Aside from this similarity, the major agents in the carbonate factories on the two platforms were quite different from each other. Northern platform sedimentation was dominated by bryozoans. Corals and coralline algae were both rare, as was *Halimeda*. On the southern platform, however, sedimentation was dominated by coralline algae, with common corals. Additionally, terrigenous input, in the form of siliciclastic sediments, was significant on the northern platform, and practically nonexistent on the southern platform.

Differences in possible accumulation rates between the two groups of biota dominant on each of the platforms likely accounts for differences in architecture and duration of the two platforms. On the northern platform, sedimentation rates would have been quite low, as bryozoans tend to have slow accumulation rates. Corals and coralline algae dominant on the southern platform have accumulation rates that are an order of magnitude greater than the biota found on the northern platform.

Photosynthetically driven calcification was the dominant process on the southern platform, while heterozoan (terminology of James, 1997) calcification was dominant on the northern highstand platform, even though the widespread presence of LBF indicates that much of the deposition on the northern platform occurred within the euphotic zone. The difference between photosynthetic calcification and heterozoan calcification probably accounts for why sedimentation on the southern platform kept pace with late-Early Miocene sea level rise, while sedimentation on the northern platform did not.

Sediments on the two platforms also differed by the mineralogy of the dominant sediment constituents on each platform. Sediments on the northern platform are largely

composed of calcite, with rare aragonite and hi-Mg calcite. On the southern platform, however, sediments composed of aragonite and hi-Mg calcite were common. These mineralogical differences speak to a difference in carbonate saturation state between the two platforms.

Carbonate saturation state was lower on the northern platform than it was on the southern platform. This can be inferred from the abundance of porcellaneous foraminifers in some units recovered from the southern platform, as well as the lack of said foraminifers in sediments from the northern platform. Similarly, zooxanthellate corals were abundant in some intervals of the southern platform, and they were rare to absent on the northern platform. One would expect, based on paleolatitude, that the carbonate saturation states of the two platforms would be reversed. Paleowater depth, combined with differences in current regimes, fluvial input and paleochemistry, likely played a critical role in decreasing carbonate saturation state on the northern platforms while increasing it on the southern platform.

Sedimentation on the southern platform took place in much shallower, more restricted environmental conditions, overall, than did sedimentation on the northern platform. The depositional environments inferred from quantitative analyses of sediment constituents on the northern platform were ranged from open euphotic to oligophotic. Additionally, drowning sequences are preserved within the sediments recovered from the northern highstand platform site (Shipboard Scientific Party, 2002), although these pelagic sediments were not investigated in my project. Depositional environments inferred from quantitative analyses of sediment constituents on the southern platform

were consistently euphotic. Subunit IIA from the southern platform is interpreted as having been deposited in a shallow restricted euphotic environment such as a sea-grass meadow.

Other environmental differences between the southern and northern platforms may include trophic resources, currents, and temperature (i.e., Kleypas, 1999; Halfar *et al*, 2004; Pomar *et al*., 2004). Trophic resources were likely higher on the northern platform, where terriginous input (as inferred from the quantity of siliciclastic grains) was significant (Shipboard Scientific Party, 2002). It is unlikely that current flow over the southern and northern platforms was significantly different, although local differences in both locations were certainly likely.

Drilling results from ODP Leg 133 on the Queensland Plateau, just north of the Townsville Trough, indicate that variations in sea-surface temperatures acted as a primary control on carbonate platform development (Isern *et al.,* 1993, 1996). Corals are stressed and exhibit reduced growth rates at water temperatures less than 24C. Results from Leg 133 (Isern *et. al.,* 1996) show that SSTs on the northeastern Australian margin are most certainly what excluded extensive coral-reef development on the Marion Plateau, although it is unclear what roles, if any might have been played by changes in oceanic circulation on the plateau. Temperature also controls carbonate platform development by changing the carbonate-saturation state of the waters (Betzler *et al.,* 1997; Pomar *et al*., 2004). At cooler temperatures, carbon dioxide is much more soluble in seawater.

Harriot and Banks (2002) examined latitudinal changes in reef development on the east coast of Australia, finding significant coral cover and diversity as far south as 31°, despite a lack of coral cover in studied areas further north. These findings, as well as the differences between the northern and southern platforms, illustrate the dangers of ascribing the presence, absence or change in biotic assemblages to climate factors alone (Pomar *et al.*, 2004).

The widespread occurrence of rhodolites in Miocene carbonates in the tropical Pacific has been attributed by Bourrouilh-Le Jan and Hottinger (1988) to a slight global drop in winter SSTs at this time, and a concomitant rise in the trophic state of surface waters of the eastern Tropical Pacific. Both of these factors are ascribed to the change in circulation patterns caused by the isolation of Antarctica and the correlated drop in global sea level (Bourrouilh-Le Jan and Hottinger, 1988). Although it would be incorrect to categorize the setting of the Marion Plateau as "tropical", especially during the Miocene, these factors surely affected the environmental conditions on the Marion Plateau, as well as the drowning of the northern carbonate platform (Site 1193).

Excellent analogues for the depositional environments of the Marion Plateau may be found in modern-day Australian waters. The southwest Australian shelf is a transition zone between tropical and temperate climates in which strong surface currents bring warm water to an otherwise temperate climatic environment (James *et al.,* 1999). Differences in water depths during active sedimentation, and resulting differences in temperature and salinity, combined with current flow, could account for differences in carbonate saturation state and therefore the biotic differences between the northern and

southern platforms. On the west Australian shelf, carbonate sedimentation in euphotic to oligophotic open-shelf environments and 20-100 m water depths is dominated by bryozoans, red algae and LBF, while zooxanthellate corals, *Halimeda* and high-Mg sedimentary constituents are rare to absent (James *et al*., 1999). In shallow-euphotic sites such as the Houtman-Abrolhos reefs, windward reefs are dominated by coralline red algae, while more restricted back reef areas are characterized by rapidly accreting coral reefs (Collins *et al.,* 1993)

Is the Assumption of the Lowstand Ramp at Site 1194 Accurate?

Paleoenvironmental interpretation of qualitative shipboard analyses was not conclusive as to the provenance of neritic sediments at Site 1194 (Shipboard Scientific Party, 2002). Quantitative analyses suggest that *in situ* shallow-water sedimentation may have occurred between 145 and 161 mbsf, however, this is not conclusive. The absence of planktonic foraminifers in some intervals interpreted to have been deposited in shallow-water at Site 1194 may indicate that these sediments were deposited *in situ*. Had the shallow-water sediments been transported to Site 1194, at least rare planktonic foraminifers would be expected as a result of bioturbation, unless the mass transport was sufficiently large to overwhelm the signal of autochthonous sedimentation. As only very few intervals lacked planktonic foraminifers, transport from the nearby platform is not

completely excluded. Moreover, the scarcity of LBF and large bryozoan debris in this interval limits the reliability of the quantitative interpretations. Further sedimentological and geochemical analyses are required to make this determination.

Benthic foraminiferal assemblages on the Marion Plateau indicate that deposition occurred between 20-50 m of water, at the top of the highstand platform, and in greater than 50m water depth at the top of the ramp deposit on the lowstand platform. In order to properly assess the change in sea level, it is imperative that the level of the highest highstand and the lowest lowstand are taken into account. The quantitative analyses in this project suggest that the level in the core that represents the lowest lowstand of sea level at Site 1194 may have occurred deeper in the core than 148.8 mbsf. John *et al*. (2004) do not explicitly choose an interval in the core recovered from Site 1194 to represent *in situ* sedimentation at that location. Rather, they seem to suggest that the entire lithologic unit is interpreted as having been deposited in 30-50 m paleowater depth. The sea-level change calculation could be revised in light of the refinements to paleowater-depth reconstructions offered by quantitative benthic foraminiferal analysis.

The most striking problem with the Leg 194 estimate of sea-level change during the Middle Miocene is that core recovery from drilling platform sediments at sites 1193 and 1194 is poor, at best (recovery was < 10%, in some intervals; Shipboard Scientific Party, 2002). The lack of recovery can make it extremely difficult to make credible statements about the platform sediments in those intervals. The lack of recovery also makes it difficult to create a usable age model for platform development on the Marion Plateau, making it much more difficult to ensure that the changes in paleoenvironment

related to sea-level change are related to the targeted second-order sea-level fall. Dolomitization of platform sediments also poses a significant challenge in meeting Leg 194 objectives, as recrystallization of platform sediments limits the ability of workers to correctly understand and interpret biological community structures preserved in Marion Plateau sediments.

Quantitative analysis of benthic foraminiferal assemblages at Site 1194 appears to reveal high-order sea-level change. Several deepening and shallowing sequences may be recorded in sediments recovered from the northern lowstand platform. Alternatively, the differences may represent changes in offbank transport from upslope.

An unexpected result

One of the most interesting results of my project was not anticipated: the tendency of foraminiferal taxa to separate out by evolutionary status in MDS space. This trend repeated itself in MDS analyses several times (see Fig. 31) and seems to suggest that Miocene taxa for which members are still extant had habitats that were more similar to each other than to Miocene-aged taxa that are now extinct. This "bottleneck" result also indicates that some ecological niches existed during the Miocene that either no longer exist in modern oceans or at least were eliminated during Late Miocene to early Pliocene

extinction events. With the abundance of changes between the Miocene environmental conditions, and modern conditions, it is difficult to posit exactly what environmental parameters might have been critical to the ecological niches that supported the extinct taxa. Another possibility is that some characteristic of still extant taxa became, at some point, important for the continued survival of those LBF taxa. Further work is required to quantify this trend, and to examine possible comparisons between the similarities of extant and extinct LBF taxa elsewhere in the world, as well as comparing the trends with LBF to other important carbonate producers – especially with corals, to see if a fundamental environmental or evolutionary change can account for this finding.

Problems, Suggestions and Future Directions for Research

To improve the accuracy of the paleoenvironmental reconstruction attempted in this project, one would need to identify the foraminiferal taxa to the species rather than merely the genus level. The foraminiferal taxa utilized for paleoenvironmental reconstruction are known to the species level (Chaproniere, 1975, 1984;Betzler and Chaproniere, 1997; Chaproniere and Betzler; Drooger, 1993). Unfortunately, species-level identification cannot be made from sedimentological thin sections but rather require precisely oriented thin sections.

An alternative approach to this problem would be quantitative assessment of morphological variation within LBF genera. In particular, two morphologies of *Miogypsina* were seen, one ovate and one vermiform. Similarly two morphotypes of *Amphistegina* were often distinguishable: the "lessonii" type and the "radiata" type. Finally, *Lepidocyclina* morphologies include eulepidine and nephrolepidine types. In each genus, one morphology tends to occur in deeper water than the other. Identifying and discriminating between morphological variations in each foraminiferal taxa would allow for a greater specificity in paleoenvironmental and paleowater depth reconstructions.

Conclusions

1. Three biofacies, representing different environmental conditions at the time of deposition were recognized on the basis of the presence and abundance of LBF taxa. The first of these biofacies consists of sediments dominated by *Amphistegina* and *Lepidocyclina*. The second biofacies recognized consists of sediments dominated by *Cycloclypeus*, *Operculina* and planktonic foraminifers. The third biofacies is dominated by porcellaneous LBF, including *Austrotrillina, Flosculinella*, soritids and alveolinids.
2. Sediments dominated by *Amphistegina* and *Lepidocyclina* are interpreted to have been deposited in euphotic habitats at probable water depths of less than 50 m.
3. Sediments dominated by *Cycloclypeus, Operculina* and planktonic foraminifers are interpreted to have been deposited in oligophotic habitats at greater than 50 m water depth.

4. Sediments dominated by porcellaneous LBF, such as *Austrotrillina, Flosculinella,* soritids and alveolinids, as well as hooked morphologies of coralline red algae, are interpreted to have been deposited in shallow, restricted, euphotic habitats, in less than 20 m water depths, consistent with a sea-grass meadow.
5. Multidimensional scaling analysis revealed a striking separation of extant LBF taxa from extinct LBF taxa, indicating that the latter utilized ecological niches that existed during the Miocene and that either no longer exist in modern oceans or were eliminated during Late Miocene to early Pliocene ecological bottleneck or extinction events.

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